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INTERSTELLAR FLIGHT

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ABSTRACT

The most significant factor in flight to the stars is the vast scale of distances involved. It would be possible, at least in principle, to construct a vehicle, deriving its power from known nuclear reactions, which would be capable of reaching the nearest stars in a period of time measured in centuries. Such a vehicle might achieve a maximum velocity of 5,000 to 10,000 km. per second. One difficult problem would be the attainment of reasonable accelerations in conjunction with the necessary high exhaust velocities. An acceleration of 0·3 cm./sec.$^{-2}$ would be adequate but would involve an almost prohibitive rate of power dissipation.

Vehicles designed to achieve velocities close to that of light would need to utilize sources of energy far more potent than any known to-day. Nothing less than the complete conversion of matter into utilizable energy would be sufficient for this purpose. The dynamics of vehicles moving at such high velocities would have to be based upon the principles of special relativity. An important consequence of this would be the reduction of voyage transit times in the traveller's system of reference. Even if one assumes the existence of power sources capable of giving vehicles velocities near to the speed of light, the attainment of useful accelerations would be a formidable problem. Accelerations of the order of 1 g would be necessary, to exploit fully the capabilities of such a vehicle and to take full advantage of the time-dilatation effect. A hypothetical vehicle propelled by photons would require to develop a useful power rating of 3 billion watts per tonne of vehicle mass (3×10^{12} watts/tonne) to obtain 1 g acceleration. If the photons were radiated from "black body" surfaces, the temperatures involved would be of the order of 100,000° C.

Interstellar matter would not provide a hazard at vehicle velocities less than 100,000 km./sec., but at near optic velocities, individual nuclei of the interstellar gas would penetrate through considerable thicknesses (>10 cm.) of solid metal and precautions would have to be taken to protect any people in the vehicle.

Introduction

Sometime in the near future, perhaps before the turn of the century, man will take his first step into space. He will do so in all probability without being unduly concerned about the chain of events which he will be setting into motion. The significance of the act may not have escaped him entirely, but he is not likely to be influenced by considerations of the ultimate importance of interplanetary travel upon human affairs. Scientific curiosity and the love of adventure for its own sake will be sufficient motives for the first exploratory voyages.

Nevertheless there must be many of us amongst the apostles of space flight to whom these two motives are only a small proportion of the whole purpose. There must be many who cannot derive complete spiritual satisfaction from the picture of mankind spending its whole existence in one single infinitesimal planet with no contact with other species who may people countless other

worlds of the universe. Many who hold to a more materialistic outlook may see in man's confinement to a single planet a factor reducing his probability of survival. Humanity dispersed over many worlds would appear more secure than humanity crowded on one single planet.

We are going to examine the possibilities of interstellar flight mainly from the latter viewpoint, viz., the possibilities of the human race establishing colonies in other stellar systems, always assuming that there are worlds suitable for mankind to be found in such systems. In other words we are concerned with the problem of getting small colonies across the almost endless interstellar gulfs, safely, but no matter how or in what time. It is not necessarily a question of getting an individual from one stellar system to another, but rather a question of getting an adequate community to another system. It is important to stress this point because this profoundly affects our interpretation of what is possible and what is impossible. For if we interpret the problem of interstellar flight as the problem of transporting a man from one system to another during his lifetime, then it is a much more difficult problem than that set by the alternative interpretation.

The problem of interstellar flight is one of vast distances and interminable transits which may demand a completely new philosophy of exploration. If we accept the more general interpretation of interstellar travel then the explorer or colonist setting out for some distant system may do so in the knowledge, not only that he will never again see his native planet, but that he will not even see the planet of his destination—a privilege reserved for his descendants. Thus the philosophy of the explorer may be that of the soldier or airman setting out on a suicide raid, doing so in the knowledge that for him there can be no personal gain, only the dying knowledge that some will survive to benefit from his action. Indeed, interstellar colonization may call for the sacrifice of whole generations in the lonely reaches of space. Colonies once established may have to exist for generations in a state of complete isolation and such communication as exists between systems may be a very tenuous and precarious matter.

Thus interstellar exploration and colonization may be vastly different from the exploration and colonization of our own world or even of our own system. It may require a revolution in our way of life not only socially but biologically if we are ever to become a galactic people.

Distance, Time and Energy

We have already indicated that the dominating factor of interstellar flight is distance, vast unimaginable distance. When we discuss the achievement of space flight, of journeys to the Moon and our solar neighbours, we talk of velocities of the order of 10 km./sec. Such velocities are insignificant on the interstellar scale of magnitudes. A vehicle leaving our system for the binary α-Centauri (at 4·3 light years distance, our second nearest neighbour), would take about 130,000 years to reach that destination if it travelled at such a low velocity as 10 km./sec. Thus the statement that vehicles capable of achieving interplanetary flight could also fly to other stars, while it may be true, is nevertheless completely academic.

It is probably true to say that interstellar flight will be considered possible

when transit times of 100 to 1,000 years can be realized, and not before then. In the case of a flight to α-Centauri or other neighbouring stars this involves mean velocities up to 10,000 km./sec. Let us see what such velocities imply in terms of known energy sources.

We will consider a rocket-propelled vehicle in which an exhaust stream with a velocity v_e is produced by some means which we need not specify. Let us suppose that the source of energy for this stream is some nuclear reaction in which a fraction α of the reacting mass is converted into energy. If the nuclear energy is converted into exhaust stream energy with an efficiency η, then for each mass m_p of propellant material ejected into the propellant stream a mass m_f of fuel must be burnt where,[1] with v_e in km./sec.,

$$\frac{m_f}{m_f + m_p} = \frac{1}{2\alpha\eta}\left(\frac{v_e}{3 \times 10^5}\right)^2 \quad .. \quad .. \quad .. \quad (1)$$

We assume that the propellant material is some comparatively cheap material which is used to give mass to the exhaust jet. It is sometimes taken for granted that the highest possible characteristic velocity would be obtained in a vehicle using a nuclear fuel "raw." However, this is not generally the case, for if we take a vehicle of empty mass m_o and some quantity ym_o of fuel, then it is easy to show that a higher characteristic velocity will be obtained if we expel some inert material with the fuel than would be the case if the fuel was used both as energy source and propellant. In equation (1) we are assuming that spent fuel is being ejected with the inert propellant, otherwise the denominator on the L.H.S. would be m_p.

Let us now see what the maximum characteristic velocity will be in a vehicle using a mass ym_o of fuel (characterized by an energy conversion factor α) to propel a vehicle of (empty mass + payload) $= m_o$. The mass ratio R is given by

$$R = \frac{m_o + m_p + m_f}{m_o}$$

$$= \left\{1 + \frac{y}{kv_e^2}\right\} \quad .. \quad .. \quad .. \quad .. \quad (2)$$

where $k = (9 \times 10^{10} \times 2\alpha\eta)^{-1}$, and $kv_e^2 < 1$.
Thus we see that:—

$$\exp.\ (v_e/v_e) = 1 + \frac{y}{kv_e^2} \quad .. \quad .. \quad .. \quad (3)$$

If we put $r = (v_e/v_e)$ then we have:—

$$y = \frac{kv_e^2\ (\exp.\ (r) - 1)}{r^2} \quad .. \quad .. \quad .. \quad (4)$$

Differentiation of equation (4) leads to the condition that y is a minimum for a given v_e. Assuming that our fuel is valuable this would be an important consideration. The condition is:—

$$\text{or} \quad \begin{matrix} r = 1{\cdot}59 \\ R = 4{\cdot}9 \end{matrix} \quad .. \quad .. \quad .. \quad .. \quad (5)$$

This condition only applies if $y \leqslant 3{\cdot}9$ (for greater values $m_p = 0$; there is no minimum condition other than $m_p = 0$).

We then find

$$v_e = 3{\cdot}4 \times 10^5 \sqrt{\alpha\eta y} \quad .. \quad .. \quad .. \quad (6)$$

Let us now examine this in terms of known nuclear reactions. Taking first of all the fission reaction, we have in that case a value of α somewhat less than 10^{-3}, so with a reasonably efficient engine we might expect $\alpha\eta = 5 \times 10^{-4}$. If we then chose a value $y = 1{\cdot}7$ we should have a characteristic velocity of 10,000 km./sec. *Such a vehicle making a one-way transit to α-Centauri would take about* 250 *years.*

As an alternative we might consider, without concerning ourselves with the practicability of it, the case of a familiar fusion reaction.

$$Li^7 + H^1 \rightarrow 2He^4 + Q$$

This was one of the first nuclear reactions ever produced artificially. The value of Q is 18·6 m.m.u. whence $\alpha = 2{\cdot}3 \times 10^{-3}$, approximately three times as great as the value for fission. If in this case one takes $\alpha\eta = 1{\cdot}5 \times 10^{-3}$ and $y = 2{\cdot}3$ then the value of v_e becomes 20,000 km./sec. and the transit time quoted above might be halved.

There are no known exothermic nuclear reactions which will improve substantially upon this performance. The most energetic fusion reaction,

$$4H^1 \rightarrow He^4 + 2e^+$$

which occurs in our Sun and other stars by way of the Bethe carbon cycle, has a value of $\alpha = 6{\cdot}1 \times 10^{-3}$ while, almost as energetic, the reaction:—

$$He^3 + H^1 \rightarrow He^4 + y$$

takes place with the evolution of 24·4 m.m.u. of energy, corresponding to $\alpha = 5{\cdot}3 \times 10^{-3}$, but since He^3 is a very rare material compared with say Li^7, one would probably not be able to obtain characteristic velocities as great as 2×10^4 km./sec. because one would be compelled to employ small values of y.

It is worth noting that in all the above cases we have derived the characteristic velocities on the basis of classical mechanics. Only in cases in which α exceeds 10^{-2} do we need to introduce relativistic theory unless we are attempting to make calculations to much better than 1 per cent. (a futile procedure in this article). In the past a number of papers on atomic energy for rocket propulsion have been preceded by a summary of Ackeret's "relativistic rocket theory," a procedure which is completely absurd insofar as the values of α for all known exothermic nuclear reactions (as we have seen above) are such that the relativistic theory is an unnecessary refinement. We will, however, return to the problem of flight under relativistic conditions at a later stage in this discussion.

Before proceeding we might well pause to consider the nature of the propulsion unit which would raise our interstellar vehicle to the considerable velocities which we are contemplating. Let us take a closer look at a vehicle having a characteristic velocity of say 10,000 km./sec. Under the optimum conditions and for $y \leqslant 3{\cdot}9$ as we have shown, the exhaust velocity would be $v_e/1{\cdot}59$, i.e., 6,300 km./sec. In a voyage lasting 250 years we could afford to spend 100 years in accelerating and decelerating; this would add only 100 years

to the transit time. This corresponds to an acceleration of 100 km./sec./year or 0·31 cm./sec.$^{-2}$ (0·32 milligee). The specific exhaust power, i.e., the useful mechanical power in the exhaust jet per unit mass of vehicle, is given by the expression[1]

$$p = 4{\cdot}9 \times 10^3 a v_e \text{ kilowatts/tonne},$$

where v_e in km./sec. is in this case 6,300 km./sec. and a the acceleration in g units is $3{\cdot}2 \times 10^{-4}$. Hence $p = 10$ Megawatts/tonne.

This represents a very severe power requirement and is certainly not one which could be met by present-day engineering technology. It is difficult to visualize engines running at such a high power level for 50 years continuously. However, it is to be expected that interplanetary flight techniques will have reached a very advanced state before man will be ready to embark upon deeper space flight, and low thrust/high exhaust velocity vehicles may have had several hundred years of development before they are called to play this more exacting role.

In all probability the vehicle which will carry our descendants on their first mission to the stars will use the ion-rocket principle, unless of course some new "subtle engine"* of yet unconceived principle is forthcoming by that time (and it is always dangerous to rule out such possibilities). It is not necessary to go into the principles of the ion-rocket in this discourse, as these have been covered in a number of earlier papers.[2,3,4] However, we may note that a singly charged ion of atomic weight M accelerated through a voltage V reaches a velocity v_e given by

$$v_e = 14\sqrt{\frac{V}{M}} \text{ km./sec.} \quad .. \quad .. \quad .. \quad (7)$$

To obtain an exhaust velocity of 6,300 km./sec. using carbon ($M = 12$), for example, as inert propellant, we should require an accelerating voltage of 2·5 Megavolts.

It is quite possible, in view of the high specific exhaust power required, that a great deal of the inert propellant carried by the interstellar vehicle would consist of power plant and propulsion unit replacements. From time to time during the acceleration programme old worn-out (and probably burned-out) plant could be stripped out and consigned to the ion sources. As the voyage neared its termination and the all-up mass was reduced, the number of propulsion units might be reduced by a similar process. In this way nearly all of the initial dead weight of the vehicle would serve some useful purpose in addition to its use as propellant.

To summarize the facts which have been presented so far, it may be said that they show that flight to the nearest stars appears to be possible in principle provided we are willing to accept transit times greater than 100 years, and possibly 1,000 years. This achievement can be visualized in terms of existing principles though the techniques in applying these principles would have to be advanced considerably beyond the present-day level.

At first sight the idea of advancing mankind's frontiers to points requiring

* *Vide* C. S. Lewis, *Out of the Silent Planet.*

hundreds or even thousands of years to reach, might seem hopeless. It cannot indeed be regarded as a particularly satisfactory picture of interstellar exploration. However, regarded in terms of geological eras, centuries or millennia are small intervals, and provided that human life can be sustained in the exploring vehicles for such long periods, there is no reason why interstellar expansion should not proceed on this basis. An important factor in determining whether this state of affairs was adequate would be the frequency of occurrence of planets suitable for human habitation. Many theories of planetary origin suggest that only a comparatively infinitesimal proportion of the stars are blessed with planets. This being the case we might have to go much further afield than α-Centauri to find alternative accommodation for mankind. However, no theory of the formation of planets, so far advanced, can be regarded as satisfactory and for all we know planets may be the rule rather than the exception. Recent observations on the binary stars 61 Cygni (10·7 light years) and 70 Ophiuchi (12 light years) have indicated that non-luminous bodies of almost planetary dimensions are associated with both systems. If indeed two such close stars have planets it might well indicate that planetary systems are by no means rare phenomena and among the score or so stars which lie within about a dozen light years of our own Sun there may be many planets. One thing is certain, namely, that an expensive expedition taking a small community on a thousand-year voyage to another star, would not start unless it was certain that the star possessed planets of more or less terrestrial characteristics. Thus the era of astral exploration must be preceded by a period of observational astronomy the like of which we could not contemplate to-day. Instruments of performance vastly superior to those known at present would be required to survey the neighbourhood of the nearest stars. The problem would be to resolve planetary images separated from the primary images by perhaps no more than 0·5 seconds of arc, the planetary image having perhaps a strength of $<10^{-9}$ of the primary image. No telescope in existence to-day could give this performance or anything remotely approaching it, for although a moderate telescope of about 12 in. aperture could resolve two stars with this separation, the resolution of two fringe systems (the Airy Diffraction patterns, which represent the two images) when the central maximum of the one has an intensity of 10^9 times that of the other is quite a different matter. However, the eventual construction of giant telescopes on the Moon or other comparatively airless bodies might make such observations possible. Even so it might not prove possible to do any more than measure the orbits of planets detected in this manner, observe their spectra and obtain rough values of size on the basis of reflected light intensities. A more detailed survey might require an expedition to the system in question with provision for return unless the exploring party was provided with means of signalling its findings over the vast distance separating it from the home planets.

The author is not competent to deal with the biological problems of life on an interstellar vehicle undertaking a voyage lasting for a millennium. Obviously they would assume a magnitude quite as great as the engineering problems involved. In the normal way, some thirty generations would be born and would die upon the ship. It would be as though the vessel had set out for its destination

under the command of King Canute and arrived with President Truman in control. The original crew would be legendary figures in the minds of those who finally came to the new world. Between them would lie the drama of perhaps ten thousand souls who had been born and had lived and died in an alien world without knowing a natural home.

Perhaps this picture might change as a result of advances in medical science which are not yet visualized. It would be idle for a physicist to speculate upon possibilities which might exist in this field and it is no purpose of mine to do so.

It is obvious that a vehicle carrying a colony of men to a new system should be a veritable Noah's Ark. Many other creatures besides man might be needed to colonize the other world. Similarly, a wide range of flora would need to be carried. A very careful control of population would be required, particularly in view of the large number of generations involved. This would apply alike to humankind and all creatures transported. Life would go on in the vehicle in a closed cycle, it would be a completely self-contained world. For this and many other obvious reasons the vehicle would assume huge proportions: it would, in fact, be a very small planetoid, weighing perhaps a million tons excluding the dead weight of propellants and fuel. Even this would be pitifully small, but clever design might make it a sufficiently varied world to make living bearable.

The passage of perhaps thirty generations would pose major problems of a sociological nature. The control of population would be only one of many. Children could only be born according to some prearranged plan, since overpopulation or underpopulation would be disastrous. The community would be subjected to a degree of discipline not maintained in any existing community. This isolated group would need to preserve its civilization, hand on precious knowledge and culture from generation to generation and even add to the store of science and art, since stagnation would probably be the first step to degradation.

On the technical side one would list the conservation of habitability as one of the major undertakings. Maintaining a reasonable atmosphere over the long period of space flight would be no small matter. Loss of air from the vehicle, and of other volatile materials for that matter, could be very serious when integrated over a thousand years. A hundred milligrams of air leaking out of a million ton vessel in one second sounds insignificant, but in 1,000 years it would amount to a loss of 3,000 tons of material. Artificial gravity would need to be provided by rotation and one might visualize the vessel as a huge oblate spheroid. The list of problems could be increased endlessly but they would all add up to the fact that an interstellar expedition under such circumstances would be formidable indeed.

Flight at Near-Optic Velocity

Thus far we have confined our attention to a conception of interstellar flight based upon known principles, although involving considerable extrapolation from present technical capabilities. This has been characterized by a picture of voyages taking centuries or millennia to complete, entailing a strangely planetless existence for the travellers. This is not the notion of interstellar

travel envisaged by many people to whom even the speed of light would be an irksome crawl. Since we are in no position to judge what sources of energy will be exploited in the remote future it is essential that we should investigate some of the features of flight at velocities approaching that of light itself.

It is an observed fact in our physical world that the speed of light in empty space is a constant and that no change in the motion of the Earth relative to other heavenly bodies results in any measurable change in this velocity. This fact led Lorentz, Fitzgerald and others to formulate new equations of motion which were later moulded into the special theory of relativity by Einstein. These equations of relativistic dynamics govern the motion of all bodies at relative velocities up to that of light. At low velocities the relativistic laws merge into the familiar classical laws of Newton. It is no purpose of ours to go into the details of the special relativity theory here, we are merely concerned with its bearing upon interstellar flight.

A consequence of the relativistic laws of dynamics, which is usually regarded as setting a limitation upon flight to the stars, is the limiting nature of the velocity of light. In classical theory if a body is moving with a velocity v (observed in some fixed system of reference) and if its velocity is increased relatively by a velocity u in the same direction, then in the original system of reference its velocity is $v + u$. Thus by addition of velocities any velocity up to ∞ can be attained. However, according to relativistic laws of kinematics the resultant of this velocity composition would be:—

$$w = \frac{v + u}{1 + uv/c^2}$$

Thus if a vehicle moving with a velocity $v = 0{\cdot}9c$, in some fixed system of reference, increases its speed relatively (i.e., in a system that was initially moving with it at $0{\cdot}9c$) by $0{\cdot}1c$, its speed in the fixed system has in fact become not $w = c$ but $w = 0{\cdot}918c$ and no matter how many increments of velocity it receives in this way the vehicle could never attain the absolute velocity $w = c$.

Two interesting facts become apparent from a consideration of the relativistic laws of motion. The first is that the apparent length of a rigid body in motion with respect to a fixed system with a uniform velocity v, is reduced by a factor $\gamma = \sqrt{1 - v^2/c^2}$ along the direction of motion; by this we mean that if $\delta x'$ is the length of the moving body in the direction of motion, then the length measured by an observer at rest in the fixed system is δx where

$$\delta x = \gamma \, \delta x'$$

This effect is known as the Fitzgerald-Contraction. The second effect of note is the time-dilatation. If dt' is the time between two events recorded by a clock on the moving body then the corresponding time recorded in the fixed system would be dt where

$$dt' = \gamma \, dt$$

If, for example, the moving body was observed to traverse the distance between two fixed points in space in a time t as measured by an observer at rest, the time recorded by an observer moving with the body would be less by the

factor $\gamma = \sqrt{1 - v^2/c^2}$. This effect has been checked experimentally by observations on μ-mesons passing through the Earth's atmosphere. Cosmic ray primaries entering the atmosphere interact with the oxygen and nitrogen nuclei with the production of π-mesons which decay rapidly into μ-mesons. A typical μ-meson might have a kinetic energy of 3,000 Mev corresponding to a value of γ equal to 1/30 ($v \simeq 0{\cdot}9995c$). Now it is known that a μ-meson decays into an electron with the emission of gamma radiation and neutrinos. The mean life of a μ-meson at rest is $2{\cdot}1 \times 10^{-6}$ seconds. A μ-meson travelling at the velocity of light would traverse 600 metres in this time. The average height of formation of μ-mesons is 16 km., and if the mean distance traversed were only 600 metres, then only an immeasurably small proportion would reach the surface of our Earth. In point of fact a large proportion reach the surface, a fact which can only be explained on the basis of the time-dilatation effect.

The interesting feature of the time-dilatation effect as it affects interstellar flight can be illustrated by considering the voyage of a hypothetical space traveller, whom we may call X, who travels from the Solar system to some other star with a constant velocity v and returns with the same speed. Supposing a second observer Y who remains at rest in the Solar system records a time t for this voyage, then if we assume that the periods of acceleration, retardation and rest at the destination were negligible, X will record a time t' where

$$t' = t\sqrt{1 - v^2/c^2}$$

To take an example, suppose X goes from our system to Procyon (10·4 light years) and back with a velocity $0{\cdot}990c$. γ takes a value of 1/7 at this velocity. The result is that, while the observer Y records X's return 21 years later, X is aware only of a passage of *3 years*. Indeed if X could get close enough to the speed of light he could circumnavigate the universe in his life-time, though he would find on returning that perhaps 10^{10} years had elapsed and the Solar system and stars that he knew had changed beyond recognition. This would in fact be one-way time travel.

Clearly, the attainment of velocities close to that of light would make interstellar travel a much more promising proposition than would the speeds which we have considered in the first part of this discussion. It would become possible for a man to leave his native system, journey to a star—even fairly distant ones would be within reach—and return within a few years of his time. The only shortcoming would be the fact that a long time would actually have elapsed at home during his seemingly short voyage, and friends whom he left in the bloom of their youth would be found in their dotage. It is possible that human society, with the help of medical science, could adapt itself to such a state of affairs, but it is no purpose of mine to speculate on such matters here.

The first requirement of a vehicle designed to reach velocities close to that of light would be a source of energy far more potent than anything known to-day. The best that we could imagine in terms of our present day knowledge would be the wholesale conversion of mass into energy. In modern nuclear and cosmic ray physics we know of a small number of processes whereby particles are completely converted into radiation, the oldest known process being the mutual annihilation of the electron and position, with the complete conversion

of their mass into electromagnetic energy in the form of two equally energetic photons. It is not known whether nucleons (i.e., protons and neutrons) can undergo similar processes; searches for the negative proton have so far proved fruitless. However, it is possible that such a particle can exist, if only for a short time, in which case the complete conversion of nuclear matter into energy is possible at least in principle. It would be quite pointless to speculate upon the possibilities of releasing energy in useful amounts by annihilation, since there is no process known to us to-day which might produce such an effect. However, in the appendices we have derived the equations of rockets taking their energy from such sources.

We have supposed that a rocket starts from rest with some mass M_o and then proceeds by reducing this mass, part of the mass being ejected to form the propellant stream and part being converted into the energy required to expel this stream. A case which is of particular interest is that in which all the mass loss goes into energy, the propellant stream consisting of a beam of photons. It is shown that the equation (A.15) governing the motion of this vehicle would be

$$v'_e = -\eta c \, ln(M_o/M)$$

where η is the efficiency of energy conversion, i.e., the fraction of the energy released, which is directed usefully into the exhaust stream and c the velocity of electromagnetic radiation. The velocity v'_e is not the actual velocity attained by the rocket relative to the system in which it was initially at rest, but is a quantity which would be recorded by a speedometer in the vehicle, if that instrument worked by integrating the acceleration with time making no allowance for relativistic effects. It is given by

$$v'_e = \frac{c}{2} \, ln \left[\frac{c+v}{c-v}\right]$$

where v is the true velocity (cf. Eqn. A.11).

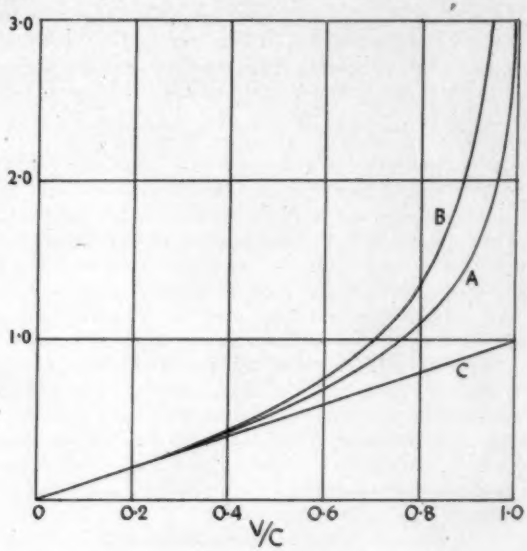
The occurrence of the factor η in the above equation arises from the fact that wasted energy is equivalent to matter dumped uselessly outside the vehicle with zero velocity. Thus in the more familiar case of low velocity rockets such as we have to-day, if we allowed a fraction $1 - \eta$ of our propellant to leak uselessly out of the rocket while only the remainder went usefully into the jet we should obtain a similar expression to the one above.

In a photon rocket, of course, the value of η would depend upon the manner in which *all energy* leaving the rocket was directed, and one can imagine a system of mirrors so disposed that all "waste heat" leaving the vehicle was directed opposite to the direction of motion. It would then cease to be waste heat but would become a useful part of the propellant stream. Thus the value of η would tend to unity.

A comparison of the classical and relativistic equations of motion shows that while the latter places restrictions upon interstellar flight from the point of view of the stationary observer, because of the time-dilatation effect it actually favours the traveller. To illustrate this we shall consider a vehicle having a mass ratio of 7·4, driven by photons with $\eta = 1$. We then have

$$v'_e = 2c$$

If the classical theory applied, this vehicle would be capable of accelerating to the speed of light and then coming again to rest. Supposing the periods of acceleration to be negligible, then the time to reach α-Centauri for example would be 4·3 years.



A $v'_a/c = \frac{1}{2} ln \left(\frac{c+v}{c-v}\right)$

B $v_a/c = 1/\sqrt{1 - v^2/c^2}$

C v/c

FIG. 1.

In the relativistic theory, however, we see from Fig. 1 that the actual velocity reached by the rocket will be 0·76c, whence in the rest system the transit time would be 5·64 years. On the other hand the transit time in the traveller's frame of reference is only 3·67 years. Thus when we speak of the principles of relativistic mechanics being a barrier to interstellar flight, we are not being strictly correct. The most serious factor restricting journeys to the stars, indeed, is not likely to be the limitation on velocity but rather limitation on acceleration. We have already shown that a vehicle employing an exhaust velocity of 6,300 km. per second would require a specific exhaust power of 10 Mw/tonne to give an acceleration of 0·32 milligee. In the case of our photon rocket the specific exhaust power would be (in the case $\eta = 1$):—

$$p = 3{,}000\ a' \text{ Megawatts/tonne}$$

where a' is the acceleration of the rocket in a system instantaneously at rest with respect to it (this is obtained from equation A.7a in the appendix), a' is in

cm./sec.^{2} This is a factor of 100 worse than the previous case quoted because of the much higher exhaust velocity (and an unfavourable factor of 2 which creeps into the expression for p as $v_e \to c$). We see that a photon rocket accelerating at 1 g would require to dissipate power in the exhaust beam at the fantastic rate of 3 million Megawatts/tonne. If we suppose that the photons take the form of black-body radiation and that there is 1 sq. metre of radiating surface available per tonne of vehicle mass then we can obtain the necessary surface temperature from the Stefan-Boltzmann law, which would give

$$5{\cdot}7 \times 10^{-8}\, T^4 = 3 \times 10^{12} \text{ watts/metre}^2$$

in this case, where T is in degrees Kelvin. In other words, our emitting surface would have to be at a temperature of about 100,000° K. It might be argued of course that the radiation need not be black-body radiation but could be generated in the form of radio waves. However, unless we could make the efficiency of the generating cycle equal to unity we should be faced with the problem of disposing of the "waste heat" in the form of thermal radiation, which would again involve high temperature emitting surfaces. Besides this, one has the fact that photons emitted as black-body radiation represent energy in its most degraded form and there would be far less difficulty in obtaining the high ratings in this case, than if one had to employ some complicated conversion cycle to obtain a more artificial form of energy (such as electrical energy).

The inevitable conclusion from this, is that even if we assume the possibility of a source of energy involving the complete conversion of matter into photons, we should still be faced with what, in terms of present day science, would be an insurmountable obstacle, viz., the impossibility of producing useful accelerations, i.e., $\sim 1\, g$. If we were forced to rely upon "milligee" accelerations (or less) then the transit times to the nearest stars would again be brought back to periods measurable in centuries, despite the high ultimate velocities. For example, if we consider a vehicle proceeding half way to α-Centauri with a continuous acceleration of ·001 c/year (approximately 1 milligee) and then an equal retardation over the remainder of the voyage, we find that it would take 130 years and reach a maximum velocity of only ·065 c (19,500 km./sec.).

It is clear, therefore, that the limiting nature of the velocity of light is not necessarily the most serious barrier in the attainment of interstellar flight, in fact in most respects it is no barrier at all. The real difficulty, always assuming that we can find suitable energy sources for the job, lies in the unfavourable ratio of power dissipation to acceleration as soon as we become involved with high relative velocities. The problem is fundamental to any form of propulsion which involves non-conservative forces (e.g., the thrust of a rocket jet) to produce the necessary acceleration. The only method of acceleration which one can conceive that would not be subject to this difficulty, would be that caused by an external field of force.

It might be argued of course that emitters at a temperature of 100,000° K. are not fundamentally impossible and that such temperatures are not even outside the range of our experiences to-day. However, the fact is, that the utilization of radiators at this temperature is quite inconceivable in terms of existing techniques and we are therefore in no position to speculate profitably

on its ultimate feasibility. We can merely point out that this is a fundamental requirement which would have to be met in a vehicle utilizing an exhaust velocity $\approx c$ and accelerations $\approx 1\ c$ per year.

The Effect of Interstellar Matter

As soon as we consider motion through space at velocities which are comparable to that of light, we find that we can no longer regard interstellar space as a complete vacuum. Interstellar matter is known to exist with an average density equivalent to about 1 hydrogen atom per cm.^{3}, though with variations of up to 1,000 between regions of lowest and highest densities. This matter occurs in two forms, (*a*) the interstellar gas, and (*b*) interstellar dust, it being probable that the latter accounts for ~ 1 per cent. of the total interstellar matter which consists mainly of gaseous hydrogen and helium.

Ovenden[5] has examined the possibilities of collisions between an interstellar vehicle and the dust particles. He has found, on the basis of the available evidence, that the probability of collision of a particle of radius $>4 \times 10^{-5}$ cm. and a vehicle of 100 sq. metres cross-section moving at 10^{10} cm./sec. is so low that only one collision would occur in 10^{11} years. This constitutes no risk at all. Collisions with dust particles of smaller dimensions can be considered in conjunction with collisions of individual atoms, especially at near optic velocities when the distance of penetration of a very small particle is probably almost identical with the mean range of the individual nuclei in the target material. We shall confine our attention to encounters between the vehicle and the interstellar gas.

If we have n particles per cm.^{3} in the space through which a vehicle is moving with velocity v cm./sec., then the vehicle is in fact being bombarded from the front by a flux of nv particles/cm.^{2}/sec. At the speeds which we have been considering this corresponds to fluxes $\sim 10^9$–10^{10} protons/cm.^{2}/sec. and smaller numbers of α-particles and heavier nuclei. (The electrons accompanying these particles can be ignored since they carry a negligible fraction of the energy carried by the nuclear particles.)

At a speed of 14,000 km./sec. a proton striking the vehicle has an energy of 1 Mev. A flux of 10^9 protons per cm.^{2}/sec. with this energy would produce no serious effect, the range of a 1 Mev proton in air being only 2·5 cm. (a helium nucleus at the same velocity would have the same range and other nuclei would have ranges $\propto M/Z^2$), so it would penetrate only a few microns into the hull. A small amount of radioactivity would be produced as a result of nuclear disintegrations caused by the bombardment, but it would be of no consequence. In the non-relativistic region the range of penetration of particles into the solid material of the hull is roughly proportional to the (velocity)^3, and on this basis we see that a hull 1 cm. thick of some material such as aluminium would be effective protection even at velocities up to 100,000 km./sec.

The problem becomes serious at velocities of 200,000 km./sec. or more, when the oncoming particles represent a flux of "cosmic radiation" about 10^{11} times as intense as the flux at the top of our atmosphere. The ranges of these particles now assume values measured in kilometres of air at N.T.P. and considerable

thicknesses of solid matter become necessary to bring them to rest. It would prove necessary to dispose a considerable mass of material in front of the living quarters of any vehicle travelling at near-optic velocities. This material could of course be used up in the closing stages of the retardation programme when the velocity had been reduced to a safe level.

The actual flux of mass into the front of the vehicle is small ($\sim 10^{-10}$ gm. per square metre per second) and could produce no detectable retardation effects. Similarly the energy flux (~ 1 watt/cm.^{2} at $\frac{3}{4}$ of the speed of light) would be comparatively small though it would raise the temperature of the bombarded surface by several hundred degrees Centigrade unless the heat was conducted away and distributed over a much larger surface.

It is evident from the above considerations that the existence of interstellar matter could not be ignored in vehicles travelling near the speed of light. Precautions would have to be taken to ensure that the interstellar particles or any of the secondary radiations (mesons, etc.) produced by them could not penetrate to the living quarters, and that the heat produced from these particles did not result in excessive temperatures within the vehicle.

Conclusions

There does not appear to be any fundamental reason why human communities should not be transported to planets around neighbouring stars, always assuming that such planets can be discovered. However, it may transpire that the time of transit from one system to another is so great that many generations must live and die in space, in order that a group may eventually reach the given destination. There is no reason why interstellar exploration should not proceed along such lines, though it is quite natural that we should hope for something better. To achieve a more satisfactory performance, however, we should need sources of energy far more powerful than any utilized or known to-day. Nothing less than the complete conversion of matter into energy would suffice to bring about speeds where the traveller could exploit the relativistic time-dilatation effect which would reduce interstellar transit times to quite moderate proportions. Even if we assume that such energy conversion will become possible it is by no means certain that we should be able to make effective use of it. A probable stumbling block in this direction is the extremely unfavourable ratio of power to acceleration which results from the use of exhaust velocities approaching the speed of light. It is quite impossible at the present time to come to any conclusion regarding the possibility of interstellar flight along these more ambitious lines.

The notion that the impossibility of velocities greater than c places any serious restriction upon interstellar communication, is based upon a rather narrow outlook. It is true that if we think in terms of interstellar vacations, business trips to Capella and interstellar warfare a certain inconvenience would be encountered. But these are minor features, and taking the broad view of things, the fact that it may take many years to go from one system to another is no great restriction. Indeed, so far as the traveller is concerned the limiting nature of the speed of light is more than offset by the time-dilatation effect;

from his viewpoint the speed of light is infinite. And, though man can never travel faster than light, his frontiers will be limitless if he can approach it ever closer.

APPENDIX

1. Relativistic Equations of Rocket Motion

Let v_e be the exhaust velocity of the rocket, suppose that m is the rest mass of propellant ejected in unit time from the rocket and a' the acceleration of the rocket, measured in a co-ordinate system which is instantaneously at rest with respect to the rocket. Then a' is given by the equation

$$Ma' = -\frac{mv_e}{\gamma_e} \quad .. \quad .. \quad .. \quad \text{(A.1)}$$

where M is the rest mass of the vehicle at the time in question and

$$\gamma_e = \sqrt{1 - \frac{v_e^2}{c^2}}$$

The equation giving the rate of energy dissipation in the exhaust beam is, by a well known relationship of relativistic mechanics,

$$\frac{dE}{dt'} = mc^2\left\{\frac{1}{\gamma_e} - 1\right\} \quad .. \quad .. \quad .. \quad \text{(A.2)}$$

The time t' used in this equation is that measured in the rocket.

The specific exhaust power P ($\equiv dE/Mdt'$) is given by the equation

$$P = ca'\sqrt{\frac{1-\gamma_e}{1+\gamma_e}} \quad .. \quad .. \quad .. \quad \text{(A.3)}$$

It is easily seen that for very small v_e this goes to the familiar form $P = av_e/2$ and as $v_e \to c$, $p \to ca'$.

If we assume that energy is derived from matter then we may characterize the process as we have done earlier in the text by a conversion factor α.

Suppose $\frac{dM}{dt'}$ is the rate of loss of rest mass of the rocket, then $\alpha\frac{dM}{dt'}c^2$ is assumed to be the amount of power generated, the remainder $(1-\alpha)\frac{dM}{dt'}$ is the mass discharge rate in the exhaust, i.e.,

$$m = (1-\alpha)\frac{dM}{dt'} \quad .. \quad .. \quad .. \quad \text{(A.4)}$$

If η is the efficiency of conversion of the total generated power into useful exhaust power then from the equivalence principle

$$\frac{dE}{dt'} = \eta\alpha\frac{dM}{dt'}c^2 \quad .. \quad .. \quad .. \quad \text{(A.5)}$$

The remaining energy $(\eta - 1)\alpha\frac{dM}{dt'}c^2$ is assumed to be discarded as waste

heat, etc. The loss of this energy would represent of course a waste of the mass transported by the rocket and would be analogous in the classical case of low velocity rockets, to the discarding of material from the rocket at zero relative velocity. Ackeret,[6] in deriving his relativistic rocket equations, ignores this wasted mass and his final equations are consequently only applicable in the case $\eta = 1$.

Combining Eqns. (A.2), (A.4) and (A.5) we find that

$$\gamma_e = \frac{(1-\alpha)}{(\eta\alpha - \alpha + 1)} \quad .. \quad .. \quad .. \quad \text{(A.6)}$$

Eqns. (A.3) for the specific exhaust power then becomes

$$P = ca' \sqrt{\frac{\eta\alpha}{2-(2-\eta)\alpha}} \quad .. \quad .. \quad .. \quad \text{(A.7)}$$

If a' is in cm./sec.$^{-2}$, then

$$P = 3{,}000\ a' \sqrt{\frac{\eta\alpha}{2+\eta\alpha-2\alpha}} \text{ Megawatts/tonne} \quad .. \quad \text{(A.7}a\text{)}$$

Returning to Eqn. (A.1) we note that the acceleration a' relative to a system which is instantaneously at rest with respect to the rocket is given by

$$a' = -\frac{mc\,(1-\gamma_e^2)^{\frac{1}{2}}}{M\gamma_e} \quad .. \quad .. \quad .. \quad \text{(A.1}a\text{)}$$

This is the acceleration which would be recorded in the rocket by any of the inertial types of device which are normally employed in acceleration measurement. In the following we shall assume for simplicity that a' is kept constant by making $m \propto M$. Let us assume that the rocket starts from rest in some fixed system and accelerates to a velocity v. In the fixed system the acceleration a of the rocket is observed to be a function of v. In fact

$$a = \gamma^3 a' \quad .. \quad .. \quad .. \quad .. \quad \text{(A.8)}$$

Where, as before

$$\gamma = \sqrt{1 - v^2/c^2}$$

Because of the time-dilatation effect, the time t' recorded in the rocket during the period of acceleration to velocity v is different from that t recorded by an observer at rest in our fixed system. In the latter case as we easily see from (A.8)

$$t = \int_0^v \frac{dv}{a'\gamma^3} \quad .. \quad .. \quad .. \quad \text{(A.9}a\text{)}$$

While since $dt' = \gamma\, dt$

$$t' = \int_0^v \frac{dv}{a'\gamma^2} \quad .. \quad .. \quad .. \quad \text{(A.9}b\text{)}$$

Integration of these expressions leads to results

$$t = \frac{cv}{a'\,(c^2 - v^2)^{\frac{1}{2}}} \quad .. \quad .. \quad .. \quad \text{(A.10)}$$

and

$$t' = \frac{c}{2a'} ln \left\{\frac{c+v}{c-v}\right\} \quad .. \quad .. \quad .. \quad \text{(A.11)}$$

It is interesting to note that the quantity $v'_c = a't'$ is the velocity which would be given by an instrument in the rocket, basing its reading on time integration of acceleration according to classical laws. We shall refer to this as the "classical velocity deduced in the rocket." The quantity $v_c = a't$ might by analogy be called the "classical velocity deduced by the observer at rest" since it is the velocity which an observer at rest would deduce for the rocket in ignorance of the laws of relativity, i.e., assuming that $a = a'$ for all values of v. The quantity v_c is of no particular significance but v'_c is otherwise, insofar as it replaces the velocity of the rocket in the familiar expression $v = -v_e \, ln \, (M_o/M)$ as we shall now show. We have by equation (A.1*a*)

$$a' = -\frac{dM}{Mdt'} \frac{(1-\alpha)\, c\, (1-\gamma_e^2)^{\frac{1}{2}}}{\gamma_e} \quad .. \quad .. \quad \text{(A.12)}$$

Assuming a' is kept constant we have by simple integration, after taking dt' over to the L.H.S.,

$$v'_c = a't' = -\frac{(1-\alpha)\, v_e}{\sqrt{1 - v_e^2/c^2}} ln \, (M_o/M) \quad .. \quad .. \quad \text{(A.13)}$$

With the help of Eqn. (A.6) we find

$$v'_c = -\,(1-(1-\eta)\alpha)\, v_e \, ln \, (M_o/M) \quad .. \quad .. \quad \text{(A.14)}$$

This is exactly equivalent to the classical equation for low velocity rockets, for the case where a fraction $(1-\eta)\alpha$ of the ejected mass is dumped uselessly from the vehicle at zero velocity. In the case where $\eta = 1$ this equation becomes identical with that given by Ackeret (Eqn. (15), loc. cit.).

When $\alpha \to 1$, $v_e \to c$, Eqn. (A.14) becomes

$$v'_c = -\eta c \, ln \left\{\frac{M_o}{M}\right\} \quad .. \quad .. \quad .. \quad \text{(A.15)}$$

This is the equation applicable to the photon rocket in particular. The importance of high conversion efficiency is self-evident.

The quantity v'_c is plotted against v in Fig. 1. It will be noted that the characteristic velocity required in a relativistic rocket is no longer given by the sum of the actual velocity changes, but by the sum of the changes of the classical velocity deduced in the vehicle.

2. Transit Times

Suppose accelerations tend to ∞ and transits are made at constant velocity v. The time taken to cross a distance s as measured in the system at rest with respect to s is of course s/v, but in the moving vehicle it is given by

$$t' = \gamma s/v$$
$$= (c^2 - v^2)^{\frac{1}{2}} s/cv \quad .. \quad .. \quad .. \quad \text{(A.16)}$$

In other words, as we see from (A.10)

$$t' = s/v_e \quad .. \quad .. \quad .. \quad .. \quad \text{(A.20)}$$

i.e., the apparent transit time is given by substituting (in the familiar equation

$t = s/v$) the classical velocity deduced in the fixed system instead of actual velocity.

If classical laws were obeyed for all velocities, however, a given mass ratio would lead to a final rocket velocity v'_c (cf., Eqn. (A.15) above) and the transit time observed both in the system at rest and in the rocket would be

$$t_c = s/v'_c \quad .. \quad .. \quad .. \quad .. \quad \text{(A.21)}$$

Since, as we readily observe from Eqns. (A.10) and (A.11) $v_c > v'_c$, it follows that $t_c > t'$. In other words the principles of relativity actually favour the interstellar traveller, and he is able to get to his destination quicker in his own observed time, than he would be able to do in a vehicle of equal performance if the classical laws applied and there was no limit on velocities attainable.

3. Distance as a Function of Acceleration

Given the constant acceleration a' as previously defined, it is required to find the distance s moved by the vehicle while it is accelerating to a steady velocity v. Since $ds = vdt$ we have by Eqn. (A.9*a*)

$$s = \int_0^v \frac{vdv}{a'\gamma^3} \quad .. \quad .. \quad .. \quad \text{(A.22)}$$

This integral is easily evaluated, giving

$$s = \frac{c^2}{a'}\left[\frac{1}{\sqrt{1 - v^2/c^2}} - 1\right] \quad .. \quad .. \quad .. \quad \text{(A.23)}$$

It is seen that this equation goes into the form $s = v^2/2a'$ for low velocities. (A.23) may otherwise be written

$$s = \frac{c^2}{a'}\left[\left(\frac{dt}{dt'}\right)_v - 1\right] \quad .. \quad .. \quad .. \quad \text{(A.24)}$$

where $(dt/dt')v$ is the time-dilatation at the maximum velocity v. For very large time-dilatation factors the distance of steady acceleration becomes proportional to this factor.

Note that in Eqn. (A.24) if we express a' in the units "c per year," then s will be in light years, the velocity of light becoming unity. Then

$$s = \frac{1}{a'}\left[\left(\frac{dt}{dt'}\right) - 1\right] \text{ light years} \quad .. \quad .. \quad \text{(A.25)}$$

The acceleration unit *c per year* is equal to 950 cm./sec.$^{-2}$ and is therefore almost identical to the g unit.

4. Example of Application of Above Equations

To illustrate the use of the above equations we will consider a photon rocket having $\eta = 0{\cdot}8$ making the transit to Procyon (10·4 light years), assuming a constant acceleration of 1 c unit over the first half of the voyage and an equal retardation over the remainder.

We have by hypothesis $s = 5{\cdot}2$ light years, $a' = 1$, whence $(dt/dt') = 1/\gamma = 6{\cdot}2$, and $v = 0{\cdot}987\ c$ is the maximum velocity attained.

From Eqns. (A.10) and (A.11) we obtain the times to reach velocity v, viz.:—

$t = 6{\cdot}12$ years

$t' = 2{\cdot}48$ years

Also from Eqn. (A.11) we find that the classical velocity deduced in the rocket is

$v'_e = 2{\cdot}48\,c$

Whence from Eqn. (A.15) we deduce with $\eta = 0{\cdot}8$ that since the necessary characteristic velocity is $2 \times v'_e = 4{\cdot}96$, $M_o/M = 500$.

Thus the mass ratio of the rocket would need to be 500, the voyage would take 12·2 years according to an observer at rest but only 5·0 years in the voyagers' estimation. On the basis of Ackeret's equation ($\eta = 1{\cdot}0$) the estimated mass ratio would have been 144.

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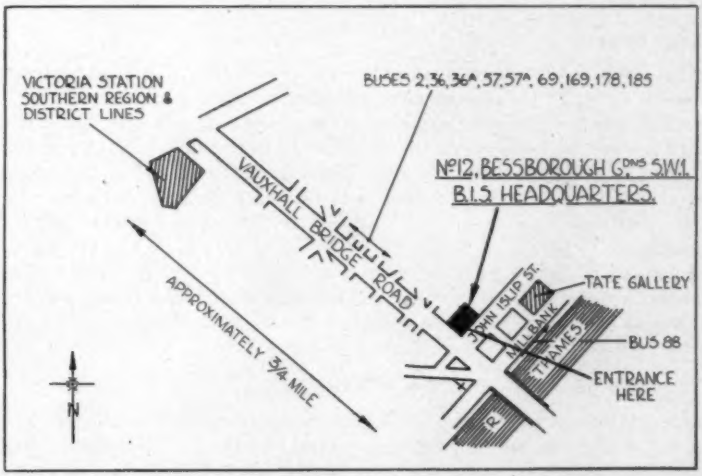
The Society's New Address



Map showing the situation of the Society's new Offices, which may very easily be reached by any bus passing along Vauxhall Bridge Road. The bus services are indicated in the top right-hand corner of the map.

ENERGY FIXATION AND INTELLIGENT LIFE

By S. S. Kind, B.Sc.

Introduction

The relative immaturity of the Biological Sciences as compared with other branches of Natural Science is reflected by the paucity of general laws by which our knowledge may be integrated into a logical whole. This lack causes much biological work to be confined into watertight compartments with a corresponding limitation of its usefulness. It also tempts the layman to hold forth on the subject and to regard the science as fair game for his pronouncements, since any attempt on his part at similar speculation in a more exact science would lead to the ridicule it usually deserves. This is not to say that speculation has no place in science, it certainly has. Useful speculation, however, keeps always in mind a basis of facts, or at least of fair probabilities, and in this way real advances may be made.

This particular paper contains a statement of some of these basic principles (along with a few opinions of the author). Its purpose is firstly to apply them to life on Earth's surface and to consider how far they may be applied on other planetary surfaces and, secondly, to stimulate the appearance of other papers on similar lines in a journal which in the eyes of a biologist must seem rather "dead."

Energy Sources

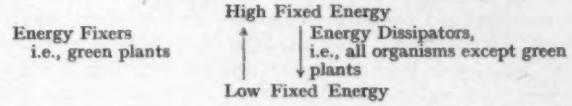
The prime requirement of all organisms is a source of energy. This they require in order to be able to carry out the functions which we recognise as typical of life, i.e., growth, respiration, reproduction, etc. In the cell this energy is stored as bond energy in the union of particular atoms and molecules and acts as a reservoir for the cell chemical reactions. It is important to understand that this energy is tied up in the union between particles and not in the particles themselves. An example in illustration of this lies in the following.

Identical amounts of carbon, hydrogen, and oxygen in the form of, on the one hand a sugar and oxygen, and on the other, carbon dioxide and water, do not possess the same amount of energy. The sugar may be burned to carbon dioxide and water thus:—

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O. \qquad \Delta H = -675 \text{ K.Cal.}$$

the energy being released as heat. This energy (released less drastically!) can be used in the cell for the organism's vital activities. The above equation represents the overall process of the total oxidation of a gram molecule of glucose. In the cell this energy is released gradually through a stepwise series of oxidation changes and not in one big lump as the overall equation suggests.

From our point of view we can divide organisms into two groups. The first is that in which the constituent organisms gain their energy from sources already fixed on the surface of the Earth. This is broadly (but not wholly*) the same as the heterotrophic group of organisms. The second group is that in which the energy is gained from a source extraneous to the earth's surface. This is broadly (but again not wholly*) the same as the autotrophic group of organisms. Calling the first group "energy dissipators" and the second "energy fixers" then the situation with regard to total fixed energy on the earth's surface utilisable by living organisms may be diagrammatically represented as follows:



The term "green plant" is here used in its botanical sense to mean all plants containing chlorophyll. As a matter of fact some "green plants" are not green in colour whilst some "non-green" plants are!

It is not to be thought that the energy fixers do not dissipate energy at all; obviously, they must do so in order to maintain their own vital activities, but the point is that they fix far more than they dissipate. Loomis[1] estimates that 15 per cent. of the total photosynthate is respired by the green plant leaving some 85 per cent. to be accounted for by other organisms.

The criterion to be accepted in determining in which group an organism is to be placed is as follows. If the chemical bond energy in the system "organism plus materials metabolised" is greater at the end of one complete and normal life cycle of the organism than at the beginning then the organism is an energy fixer; if less, an energy dissipator. Do not confuse this with the total energy resident within the organism itself for here in this restricted sense the net energy increase is always positive; that is, over a normal life cycle the organism increases in size and at death the residual dead material plus any reproductive bodies formed is greater in amount than the one reproductive body from which it came. A crude illustration of the system "organism plus material metabolized" which might serve to make the concept more understandable is the case of the mushroom and the compost heap. Here the mushroom is the organism and the mushroom plus compost heap† the system.

Assuming the compost heap to remain undisturbed, the total contained energy of the mushroom plus compost heap will decrease although that of the mushroom itself will increase as growth progresses. A comparable example with an energy fixing organism is a potted green plant.

Most organisms can be placed in one or other of these two groups but there are a few exceptions, organisms which may belong to either. An example of

* Chemosynthetic organisms such as the Iron and Sulphur bacteria gain their energy from sources already fixed but are classed as autotrophs.

† This example is inadequate when examined more closely for the system consists of all objects which exchange materials with the fungus and the fungus itself. The term "mushroom" here signifies the whole organism although normally it applies only to the fruiting body of the fungus.

this lies in some Nostoc (a blue-green alga) species which can live either photosynthetically or on organic materials dependant upon the circumstances. In the first place they are energy fixing, and in the second place energy dissipating plants.

A moment's reflection will suffice to understand that over the millions of years since organisms appeared on the surface of this planet, synthesis and decay must have been substantially equal. If not there would have been a build up of organic matter to amazing proportions or else a decrease to near zero. In the former case, incidentally, the building up process of organic energy containing materials would have been limited by the lack of elements and simpler compounds to build these despite the continued supply of solar energy. Thus all synthesis has been balanced by decay and all elements used in the organic framework have undergone and are still undergoing their own cycles, becoming more or less available for new organisms on the death of the old. A couple of examples might help here.

Anyone who has walked through a forest in which there has been a litter of dead wood will have noticed the obvious energy dissipators in the form of various fungi living on the wood. These in company with other organisms reduce the wood material eventually to its constituent elements or to simple inorganic compounds with release of its contained energy for their own use. In passing, Man's small importance in the dissipation of energy can be realized from the estimate,[1] which suggests that much less than one half of one per cent. of the energy degraded on the Earth's surface is done so by means of the Earth's total human population.

A second example which may bring these things into the familiar world is as follows. Coal is the result of arrested decay. Here the energy fixing organisms (green plants) were not fully reduced to their elementary state by the energy dissipators (bacteria, fungi, etc.). This abnormal state of affairs was brought about by conditions under which the energy dissipators could not function properly, probably oxygen lack.

We thus arrive at a picture of a cycle of continuous energy build up and breakdown with a few organisms which can take part in either but with the overwhelming majority being specialized in the direction of one or the other. This brings us on to the next topic.

Specialization

There are certain microscopic organisms which partake of both plant and animal characteristics. These organisms are simple in their makeup and may feed either by photosynthesis or by utilizing organic sources or by both. Climbing the evolutionary tree we find that the more advanced types of organisms are specialized in different directions, and so after the first major specialization into plant and animal kingdoms (roughly equivalent to energy fixers and energy dissipators respectively) other specializations take place giving us particular plant forms and particular animal forms. The vascular plant is typically specialized in the direction of living by photosynthesis and towards this end possesses flattened photosynthetic organs (leaves) which may be arranged at right angles to the incident light. Likewise the higher animals

are specialised in the possession of jaws and teeth towards the end of living on fixed stores of energy. However, do not think that all specialization is in the direction of energy utilization; an organism may be highly specialized in its reproduction or defence, etc., and man himself owes his success to specialization in the direction of increased brain power. No matter which group of successful organisms we pick we can usually note some respect in which they are more specialized than others, and in this lies the secret of their success.

Control of the Organism

In all but the simplest organisms the control of the cell's activities can be ascribed ultimately to the possession of minute discrete bodies in the cell nucleus, the chromosomes. All organic activities are directed by the interaction of the hereditary makeup of the organism (contained in the chromosomes) and the environment. Each chromosome itself is made up of a large number of units called "genes" and present work tends to show that each gene controls its own specific chemical reaction in the life of the cell.

On consideration of size alone it seems improbable that an organism may acquire new potentialities by the acquisition of new chromosomes in an indefinite fashion, that is to increase the number of its functions merely by increasing the number of its chromosomes. If this were to happen one would expect chromosome counts of thousands or millions to have arisen in the course of evolution. But this is not so. Typically the number of chromosomes in each cell in the higher plants and animals is less than a hundred.

In other words the controlling material of life is limited and the cell has to use this limited makeup in the most efficient manner possible. One can think of many reasons why this limitation is apparent, e.g., (*a*) some of the cell's activity must be devoted towards maintaining the controlling apparatus, (*b*) the highest possible surface/volume relationship must be maintained, and this necessitates small size. All this is no more or less than the cellular counterpart of specialization as we see it in the organism as a whole. The specialized organism uses its limited chromosome makeup in a special direction, the unspecialized organism in a general direction.

All this using of the terrestrial organism as a basis for argument may irritate some readers, but if extra-terrestrial life is anything like terrestrial life then the arguments will apply equally. Thus I believe that any life at all similar to life as we know it must (*a*) live by energy utilization, (*b*) self reproduce, (*c*) have its constituent units small, and (*d*) have its nature ingrained into it in a relatively stable fashion (in the same way as the gene of the terrestrial organism).

The Energy Balance

We have already noted the necessity for the equivalence of synthesis and decay on the Earth's surface, a necessity which will apply equally to any planetary surface. Thus the energy dissipating population of a planetary surface must inherently be capable of keeping up with the energy fixing population. On our own Earth's surface the gradual evolution of new forms of green plant made possible, and even necessitated, the appearance of new animals, bacteria, fungi, etc. The transmigration of plant life from sea to land and the formation

of massive land plant tissues made a tremendous impact on the nature of the energy dissipating group and it is probably not unscientific to suggest that the advent of wood (a land product) necessitated the advent of the fungi, or at least a section* of them. Although some bacteria and animals attack wood in bulk, the process is extremely slow compared to the effect produced by fungi.

Intelligent Life

Any intelligent life which may occur on another planet must be fitted to compete for existence with the other forms of life which almost certainly occur alongside it.† The question arises, which group will it belong to, the energy fixers or the energy dissipators? Now it is not beyond the limits of possibility that there may be some form of intelligent life which is its own energy fixer, or rather more crudely "a plant with a brain" (the "thinking and talking trees" of Heuer's imaginative book[2]). If this were so the organism in question would have to be so modified as to—

(1) absorb the inorganic materials of its life substance (cf. the CO^2, mineral salts and water of the terrestrial organism);
(2) absorb the radiant energy of a sun (or some other source) and utilize this to produce organic high energy materials;
(3) have a form of nervous system to pick up external stimuli, and
(4) possess a central co-ordinating body (brain) or at least a capacity, discrete or diffuse, to integrate sensory perceptions; and
(5) last of all it must be motile, for any intelligent life requires this ability in order to obtain the knowledge and materials with which to begin to fashion its own destiny.

Even if such an organism existed it would be at a great disadvantage by having to retain modifications to fix energy from an external source. Indeed it is extremely difficult to imagine what form such an organism might take.

It is not my intention to philosophize on the meaning and purpose of life, suffice to say that if there exists intelligent life on planets other than the Earth then it must be a motile member of the energy dissipating group. For any measure of success to be acquired the supply of fixed energy must not be limiting, hence requiring a synthesizing population comparable with the vegetation of the Earth.

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(2) Heuer, K., 1951, *Men of other Planets*, Victor Gollancz, Ltd., London.

* The Basidiomycetes.

† The chance of life arising on a planet and *ab initio* evolving in a straight line to an intelligent state without side branches arising must be well nigh nil. Evolution is a branching business and is the result of the selection of a few beneficial changes from a mass of random and largely deleterious changes. However, there may be a chance of a particular planet being inhabited by one form of organism only if the environmental conditions are strictly uniform over the whole surface of the planet. Such life in my opinion could not possibly be intelligent. The awakenings of intelligence arise when an organism consciously notices change. All this of course does not preclude the possibility of a single dominant life form being introduced on to a planetary surface from an outside source although, even here, the energy balance must be maintained over any lengthy period.

INTERORBITAL TRANSPORT TECHNIQUES

(with special reference to solar derived power)

By H. Preston-Thomas, Ph.D., B.Sc.

Introduction

This paper discusses the *modus operandi* of a transport system in space that has its economic justification in supplying Earth with a proportion of the rare and semi-rare metals and minerals that it needs. The writer considers that such a system, in which the transport is effected at very low cost, will be needed if space travel is to extend beyond the very occasional scientific expedition. The existence of methods of effecting such transport will also provide an incentive in addition to the present ones, which may be classed as military, scientific and telecommunication interests, for the establishment of that *sine qua non* of space travel, the manned satellite station. The present paper is not concerned with this establishment but will deal with the types of ship that operate from such a satellite, collect the raw materials and return them to Earth.

Economics

It has been suggested that raw materials from a non-terrestrial source can never compete economically with more conventional systems of production. The demonstration of the correctness or incorrectness of this statement would call for a formidable exercise in cost accounting that could never be considered to be complete owing to the fluctuating conditions imposed by technological advances. A general idea of the magnitude of the amounts of money involved, however, may be obtained from Table I, which gives recent world production and cost figures for some of the more expensive metals.

In evolving alternative sources of supply we have to consider both extraction and transport costs. As regards the former, it may be observed that deposits will be mined in the gravity-free asteroid belt or on low-gravity satellites, so that handling costs will be a minimum; that extraction from ores may take place in centrifuges giving a gravity range from zero to some upper limit; that unlimited thermal power up to temperatures of 5,000° K. is obtainable from solar mirrors at approximately zero capital cost; that electric power will be available at some capital cost—see below; that vacuum technique may be employed at zero cost; that water and atmospheric gases may not be readily available and that the history of the formation and "storage" of the minerals may considerably modify the chemical engineering problems involved. This subject will not be considered further in this paper, the remainder of which deals implicitly with the transport costs.

Methods of Propulsion

A spaceship may have velocity imparted to it by launching it from a ground station, say by electromagnetic means[1] or by a gas or rocket-driven piston

TABLE I

APPROXIMATE ANNUAL WORLD PRODUCTION AND COST OF CERTAIN METALS

Material	Annual production	Annual cost ($ × 10⁶)	Unit cost ($)
*Mercury	2,000 tons	5	2,500 per ton
*Tin	200,000 ,,	4,000	2,000 ,, ,,
*Copper	2,500,000 ,,	1,000	370 ,, ,,
*Lead	1,500,000 ,,	600	350 ,, ,,
*Zinc	2,000,000 ,,	700	350 ,, ,,
Tungsten	9,000 ,,	60	6,500 ,, ,, (in alloy)
Niobium	1,000 ,,	8	10,000 ,, ,, (in alloy)
Tantalum ..	500 ,,	10	20,000 ,, ,,
Gallium	200 lb.	0·3	1,300 per lb.
Germanium ..	1,000 ,,	0·1	100 ,, ,,
Indium	3,500 ,,	0·1	30 ,, ,,
Rhenium	100 ,,	0·25	2,500 ,, ,,

* Scarce materials, easily reduced.

working in a cylinder—see below, and it may have its velocity checked by entering an atmosphere[2]; cases where these methods may be useful are considered below. No other useful method of propelling a spaceship is known—nor does there appear to be the slightest probability that one will shortly be discovered—that does not involve the rocket principle, i.e., the ejection at high velocity of part of the ship's mass, resulting in a velocity accruing to the remainder of the ship.

The use of chemically-powered rockets of high characteristic velocity for bulk transport of material gives little prospect of ever becoming practicable owing to their high fuel consumption, even supposing that by some chance fuel can be produced on satellites or asteroids. Moreover, with one exception, thermally-accelerated exhaust gases have too low exhaust velocities at any realizable temperature to be of any practical use for this purpose. The transporting of large quantities of material with small expenditure of fuel, refueling to be readily and cheaply accomplished in space, limits the possible types of ship, in the writer's opinion, to a ship using a mixture of monatomic and diatomic hydrogen at a chamber temperature between 3,000° K. and 4,000° K., heating being by solar radiation, by solar radiation with some preheating derived from atomic energy or, and this is less likely, solely by atomic energy. This is the exception referred to above, and investigations suggests that at best it is a method of very limited usefulness, so that it will not be considered further here.

The other class of ships available are those using electrically-accelerated ions as exhaust, the electric power being derived directly or indirectly from solar or atomic power. By directly is meant the use of thermocouples or photocells in the solar case and electric fields established by β-particles, or possibly α-particles, in the atomic case. Indirectly means conversion by a boiler–turbine–generator cycle working from a mirror system or atomic pile as the case may be. Thermocouples heated atomically give a case that may be classified as intermediate. It will appear during a further consideration of

these types of drive that the accelerations they provide are so low that a convenient unit of measurement is kilometres per second per day, while it will occasionally be convenient to use units of inverse acceleration expressed in days per kilometres per second. Since the raising of the thrust above some low value may be impossible and will certainly introduce some consequent limitations in design, it will be as well to consider briefly the magnitude of the accelerations that are necessary and desirable.

Transit Times and Acceleration Requirements

The easiest, and possibly the first, journey that will be undertaken by such ships is that between an Earth satellite station and the low-gravity satellite of Mars, Deimos. It has been shown elsewhere[3] that for a low-thrust ship such a journey can be considered in three sections; the initial escape from Earth's gravitational field will require a velocity change varying roughly from 3·2 to 8 km./sec. according to the orbit used, the interplanetary journey itself will require about 8 km./sec. and from 150 to 200 days, and the approach to Deimos will require 0·6 to 1·5 km./sec. If the higher figures for the beginning and end parts of the journey are taken, their duration is of the same order as the time required for the acceleration.

For lower figures a much longer elapsed time is needed, this time increasing rapidly as the acceleration decreases. For the interplanetary section of the journey neither the transit time nor the velocity change requirements will be markedly reduced by increases in the acceleration if this is already at such a level that the velocity changes are accomplished in a time that is about half the transit time, i.e., in about 80 days. For this reason there is little point in attempting to increase the acceleration above 0·1 km./sec./day for this section of the journey and none in making it greater than 0·2 km./sec./day. (This is not to say that a higher acceleration is not desirable if a greater total velocity change, giving a shorter transit time, is used, and in practice the ship will be designed to have the optimum relation between acceleration and characteristic velocity, see below.)

Accelerations as low as this, however, will mean that a period of the order of 100 days will be required for the escape from the Earth's field, and in order that this time may be reduced without a consequent over-powering occuring for the interplanetary section of the journey, a second ship may be used for the escape, cargo transfer taking place at a considerable distance, say 500,000 km., from the Earth. A ship for such a shuttle service should be designed to have an acceleration of the order of 0·3 to 1 km./sec./day, thus reducing the elapsed time to the order of 10 to 30 days. These time and acceleration figures are applicable to manned cargo-carrying ships. Auto-directed ships may, of course, take much longer in transit and will be, therefore, easier to power, while crew transfer shuttles will have other methods of propulsion at their disposal, see below.

The design of all these ships will benefit from the fact that their structure need withstand accelerations only of the order of one milligravity or less, so that heavy bracing is unnecessary. Bracing structure will be light even

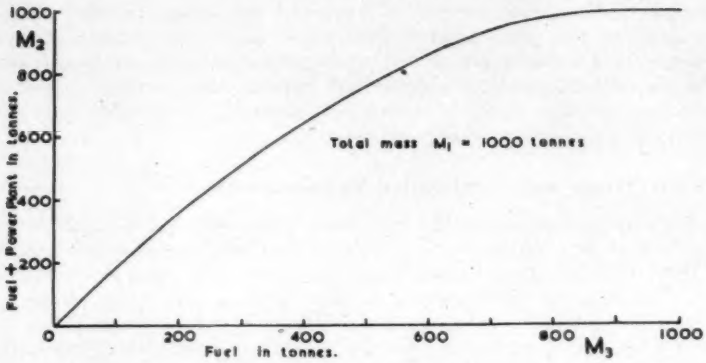

FIG. 1. Optimum proportion of fuel where output is proportional to mass of power plant and is independent of exhaust velocity.

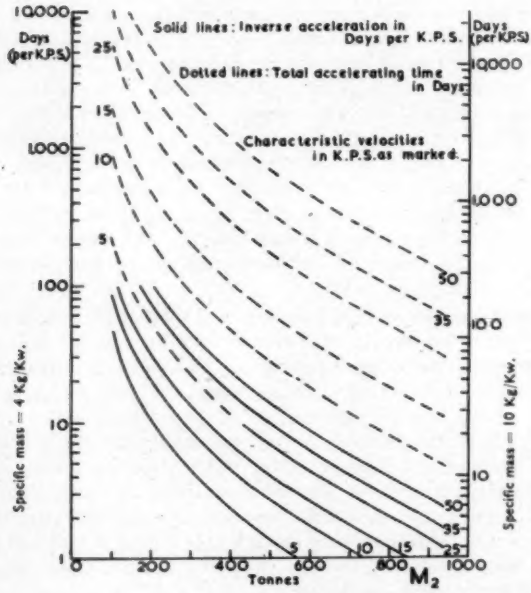

FIG. 2. Inverse accelerations and total accelerating times, for various characteristic velocities and specific masses, as functions of fuel + power plant mass (M_2); ordinate values are proportional to specific mass. $M_1 = 1{,}000$ tonnes.

in the cases where rotation of parts of a ship about an axis of symmetry provides centrifugal accelerations of 10 or more milligravities, since these stresses are directed away from a common point and can be withstood by means of light stays in tension, massive struts withstanding compressive forces being unnecessary.

General Design Data

Before considering the details of the various drive systems mentioned above we may usefully formulate some general design data that will show the expected performance and power requirements for all classes of low-thrust ships. We will take the over-all mass of any ship to be M_1 (= 1,000 tonnes in this section, other values being obtainable by proportion), of which M_2 tonnes are allocated to the fuel and the power plant, the latter term embracing everything from the prime energy collector or source to the ion guns or venturis as the case may be. It then follows that for a given M_1 and M_2 there is an optimum mass of fuel, M_3, the value of which depends on the relation of power output to power plant mass and to exhaust velocity and also on economic factors, size factors, variation of power output with time, etc. It will be shown later that in practice we may often hope to approximate to the simplest case in which power output (defined here as $\frac{1}{2}mC^2$, where m is the mass of fuel exhausted per second and C is its mean velocity along the driving axis) is proportional to power plant mass and is independent of exhaust velocity, and this case will be considered in this section.

It now becomes a simple matter to deduce the relation between the average acceleration in km./sec./day (**A**), the ship's characteristic velocity in km./sec. (V), the specific mass in kg. of power plant per kW. of power output (M_4) and the above masses:

$$\frac{1}{\mathbf{A}} = \frac{K M_2 M_4 V}{(M_2 - M_3) \log_e\left(\frac{M_1}{M_1 - M_3}\right)}$$

where K is a numerical factor. It may be seen that for a given value of M_1 the optimum value (**A** is a maximum) of M_3 is a function of M_2 only. This function is shown in Fig. 1. Thus we may see, for example, that if 600 tonnes of a 1,000-tonne ship are allocated to fuel plus power plant, 360 tonnes should be fuel and 240 tonnes power plant, these figures being independent of any other characteristic. Using these values of M_3 we can now plot 1/**A** (i.e., days per km./sec.) against M_2 for a series of values of M_4 and V. This has been done in Fig. 2, the various values of V being indicated on the curves and the two ordinate scales corresponding to the given values of M_4, other values of M_4 being obtained by direct proportion. The dotted curves show values of $Vt = V/\mathbf{A}$, the total time under acceleration for complete fuel consumption. Fig. 3 shows exhaust velocities against M_2 for various values of V, these being independent of M_4. Fig. 4 shows total power output against M_2 for a given specific mass, values for other specific masses being obtained by inverse proportion on the ordinate scale. Figs. 2, 3 and 4 are for optimum values of M_3.

One of the basic limiting factors in low-thrust ships will, in general, be the specific mass. If we assume, therefore, that this has a set value we are in a position to determine the remaining specifications. Suppose that we are confronted with the very unfavourable value of 40 kg./kW. for M_4 and wish to travel from Earth to Deimos and back, the Earth terminal being a remote (*circa* 500,000 km.) satellite station. As was indicated above, the required characteristic velocity is then about 20 km./sec., and a specification of 25 km./sec. will leave an ample safety margin.

If we now stipulate the convenient—see above—acceleration of 0·1 km./sec./day, reference to Fig. 2 shows that an impracticably small payload will result, and we therefore modify our acceleration requirement to the more realistic 0·05 km./sec./day. (This will not by any means double the duration of the journey as the proportion of coasting time is now less while the orbit has undergone considerable modification.) This requires that 80 per cent. of the ship's mass goes to power plant and fuel, a high but practicable figure. A 500-tonne ship would have 100 tonnes available for fuel tanks, general construction, food, etc., and payload. Reference to Fig. 3 shows that the

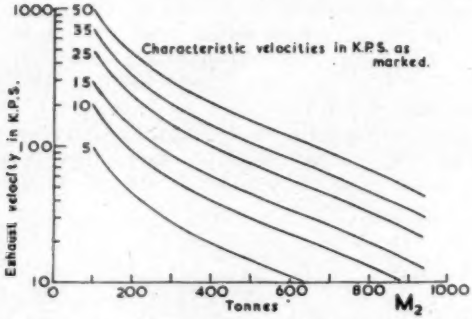

FIG. 3. Mean exhaust velocities as functions of fuel + power plant mass (M_2). M_1 = 1,000 tonnes.

required exhaust velocity is 32 km./sec. If, however, refueling takes place at Deimos (this may well be done on the initial trip since a variety of common metals may be used for fuel, and in the unlikely event of extraction proving impossible, a small fuel reserve would suffice for the return trip, provided that the exhaust velocity could be appropriately increased and that the resulting fall in acceleration was tolerable) a characteristic velocity of 12 km./sec. would be sufficient, making available in the above case, 220 tonnes for constructional and payload purposes. It seems likely, see below, that specific masses of the order of 10 to 4 kg./kW. may reasonably be expected, and reverting to our 25 km./sec. characteristic velocity at 0·05 km./sec./day acceleration, these give constructional plus payload masses of 54 and 69 per cent. of the total mass, with exhaust velocities of 80 and 135 km./sec. respectively.

Performance characteristics may be similarly derived for any given set of conditions. It should be remembered that the accelerations quoted are the characteristic velocities divided by the total time under acceleration, and since in each case thrust is constant while the mass varies, the initial acceleration is smaller and the final acceleration is higher than the quoted value, this variation decreasing as M_2 decreases. Other limitations of these design data may be more usefully discussed after a preliminary review of the various drive systems has been given (see Fig. 9).

The Ion Gun

Any rocket system requiring the conversion of electric to kinetic energy will require one or more ion guns. Since powers of the order of 10,000 kW. are used in the ships we have been considering, this section will outline some

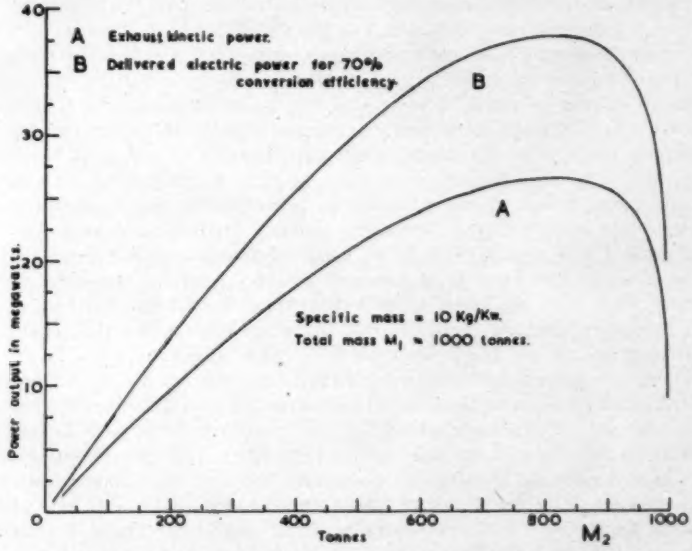

FIG. 4. Total power output as a function of fuel + power plant mass (M_2). Power output varies inversely as specific mass.

of the problems that arise in designing a unit having this power input and a high conversion efficiency; say 70 per cent. (Fig. 4 includes a curve showing delivered electric power for this conversion efficiency.) The ion guns will have to accommodate ion currents of high total magnitude, to maintain the mass/charge ratio of the accelerated particles constant within reasonable limits and to perform the initial ionization without excessive power consumption. In addition, their mass must be kept low.

This low mass requirement means that high power A.C. transformers and similar equipment cannot be used. Fortunately all the methods considered—

β-emitter, thermopiles in series, electrostatic generators—are capable of giving D.C. potentials of the order of 100,000 to 1,000,000 volts with practically no extra mass of equipment. These high voltages will be required for a number of reasons. (Ability to reach the required exhaust velocity is not one of them, as 100 volts will accelerate a singly-ionized water molecule to 30 km./sec.) Two of these are that the extremely high ion currents must be reduced as much as possible and so must the transit time of the ions in the gun. This will result in a reduction of the ion dispersion and the electrostatic shielding due to the space charge as well as reducing the demands on the ionizing system. Assuming operation at 250,000 volts, the ion beams will total 28 amp. at 75 per cent. conversion from 10,000 kW., the remaining 5 per cent. loss originally postulated being supposed to be due to velocity distribution about the mean velocity. There will be a number of ion guns, arranged so that their "density" corresponds to the ship's mass distribution. If we suppose that 140 guns are used, each gun must carry 200 mA., lose the 18 kW. of heat introduced by the conversion losses and have electrodes transmitting 200 g. weight of thrust to the ship—this last figure being for an exhaust velocity of 50 km./sec.

Beam current densities of this order can be maintained in a Finkelstein source,[4] which employs oscillating electrons emitted from a hot cathode for ionizing by electron bombardment, while pulsed beams up to 1 amp. have been obtained.[5] The main limitation in these cases is destruction of the cathode by ion bombardment, though this can be prevented by the reduction of the beam current and the use of accelerating probes. High frequency electrodeless discharges[6] can eliminate damage by ionic bombardment, but hitherto high beam currents have not been obtained by this method. Ionizing powers required vary from the order of 50 to 100 W./mA. of beam current for the high frequency discharge types to well under 10 W./mA. for the continuous Finkelstein source, cf., the estimate of 90 W./mA. above.

There are several important differences, however, between the problem under consideration and those encountered in standard atomic or molecular beam practice. It is a slight advantage that the beams we require do not have to be accurately focused and may have a high internal energy content without any marked decrease in efficiency occurring. On the other hand, instead of singly-ionized molecules we require multiply-ionized particles, the mass/charge ratio of which must be held constant within reasonable limits, particles of other mass/charge ratios and particularly uncharged particles being prevented from escaping into the exhaust. The extent to which these conditions are not observed will be reflected in an effective energy loss that is additional to the loss represented by the ionizing energy.

As an illustration of the figures involved, if we endow our fuel—presumably some convenient metal—with an atomic mass of 100, for an exhaust velocity of 50 km./sec. and an accelerating potential of 250,000 volts, each particle must have one in every 14,000 atoms singly ionized. If we can produce, say by a condensation or centrifuging process, particles of uniform size of the order of 10^{-5} cm. diameter, a "deficit" of 10^4 electrons will give a particle the proper mass/charge ratio and a surface potential due to its charge of about 200 volts. It is possible that this surface potential might serve to make the

ionizing process self-limiting; alternatively, or additionally, the selector principle of an all-electric mass-spectrometer[7] might be used to inject particles of the proper mass/charge ratio into the gun. A further difficulty is that disruption of the particles instead of their ionization may tend to occur. After they have left the gun the ions will be neutralized by electrons emitted from a hot filament. This will allow the final electrode to be at high instead of earth potential and will automatically—provided that the ions are positive ions—prevent a charge being built up on the ship.

It is obvious from this outline of the problem that owing to the several novel aspects involved, estimates of expected efficiencies based on present experiments are liable to result in considerable inaccuracies, and the suggested over-all figures of 70 per cent. conversion efficiency and $\frac{1}{2}$ kg./kW. mass/power ratio should be used with this reservation.

The mass of such guns—like the experimental difficulties—will be concentrated in the ionizing system, whether a vapourizing–condensing–charging sequence or some other system is used. An allowance of $\frac{1}{2}$ kg./kW. of output power for 28 groups of five guns each will give 250 kg. per group, which is presumably sufficient for apparatus of some degree of complexity and size. The electrodes and grids, withstanding only 200 g. weight per gun, may be of very light construction. The ion beams, however, must not be allowed to touch them since their energy is such that they will disrupt—evaporate is too weak a term—any substance on which they strike.

Electrostatic Generators

Any ion ships using indirect atomic or indirect solar power will require electric generators of very low mass/power ratio, and there seems to be little prospect of conventional generating equipment ever attaining one sufficiently low for this purpose. It seems probable, however, that some type of electrostatic generator could provide the required voltage and power output at a reasonable mass. There is a variety of electrostatic generating methods available; references to most of them will be found in a survey article by van de Graaff *et al.*[8] A modified van de Graaff generator would probably provide the best solution of the problem. Such mechanical systems, however, will be unlikely to compete with the "direct" systems, except perhaps in orbits beyond the asteroid belt, and so will not be elaborated here.

Direct Atomic Drive

The principle of this method has been described by Shepherd and Cleaver.[9] It consists of the transfer from emitter plates to collector plates of electric charge carried by β-particles, the energy of the β-particles being sufficient to overcome the high retarding potential between the plates. In this way a source of high voltage D.C. electric power is made available to the ion guns, the current to which is matched by the current carried by the β-particles. If we suppose that the emitting material is deposited on a "transparent" base with several sets of grids and collectors on either side of this base, power recovery may be of the order of 75 per cent. Fig. 5 gives a schematic diagram of such a power source. Three parallel sets of emitting plates, extended vertically and perpendicularly to the paper are shown. The number of sets

that can be placed in parallel depends on the amount of heat resulting from the conversion losses and on the permissable plate temperatures. The temperatures shown would be those resulting from a dissipation of 800 W./sq. m. of emitter with plate emissivities of 0·95. The outermost grids provide complete shielding from β-radio-activity and the inner ones permit the collection of β-particles at various energy levels. The energy distribution about the mean energy V, a complicated one where more than one β-decay takes place, will determine the precise potentials of the collector plates. The emitting plates are removable in sections for reprocessing.

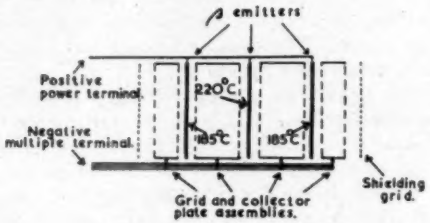

FIG. 5. β-Emitter power unit.

The choice of emitter will be governed by a variety of factors. These include availability and cost—by no means equivalent—half life, atomic weight, energy of disintegration, amount of associated γ or neutron energy, ease of handling and treatment, the transit time and the distribution of power demands throughout this time and the possibility of refueling at various points in space. Table II shows some relevant properties of a number of fission products which decay by β-emission. The significance of the yield figures will be appreciated if it is realized that the most promising material—Sr^{90}—is produced at the rate of 0·029 g./MW. day, i.e., 0·5 tonne a year, if we envisage a really atomically-minded world containing piles operating at 50,000 MW. Since with 75 per cent. recovery of power a plant of 10,000 kW. capacity will need 12 tonnes of Sr^{90}, a supply of 1 tonne per year will maintain two such power plants under equilibrium conditions. In this connection it should be noted that the emitting plates must be processed and partially renewed at intervals of the order of one-quarter of the half-life, since it is highly desirable that there should be a fairly constant power output, preventing the presence of idle mass during periods of low power. This means that for the case considered "renewal" will take place every five years at least, a convenient interval for extended interplanetary voyages. This point explains why material such as Y^{91}, produced in the same quantities as Sr^{90}, is of such limited usefulness. Although only 150 kg. of this material are required for a 10,000-kW. output, there is an equilibrium for the quoted pile system of this amount only, and emitting plate renewal should take place at intervals of about 15 days. This would not debar such a system, however, from powering an "escape shuttle" transporting materials between a near and a remote satellite station, cargo transfer to and from an interplanetary ship taking place at the latter and atomic fuel replacement at the former station. Ce^{144} is another material—

TABLE II*

TABLE OF LONG LIVED FISSION-PRODUCTS

Isotope	Yield	Half life	Maximum β energy	
Strontium 89	4·6%	55 days	1·50 Mev	—
Strontium 90 ..	5·3%	25 years	0·61 ,,	—
Yttrium 90 ..		62 hours	2·3 ,,	—
Yttrium 91	5·4%	57 days	1·53 ,,	—
Zirconium 95 ..	6·4%	65 days	0·39 ,,	γ
Columbium 95 ..		35 days	0·15 ,,	γ
Technetium 99.. ..	6·2%	10^6 years	0·3 ,,	—
Ruthenium 103 ..	3·7%	41 days	0·25 ,,	γ
Ruthenium 106	0·5%	1 year	0·03 ,,	—
Rhodium 106 ..		30 secs.	3·5 ,, (82%)	γ
			2·3 ,, (18%)	
Cesium 137 ..	6·2%	33 years	0·5 ,,	—
Barium 137 ..		2·6 mins.	—	γ-rays only
Cerium 144 ..	5·3%	290 days	0·35 ,,	—
Praseodymium 144		17·5 mins.	3·0 ,,	γ
Promethium 147 ..	2·6%	4·4 years	0·22 ,,	—

Isotopes bracketed together follow each other in a chain of disintegrations.
Isotopes marked γ also emit gamma radiation.
The β particles are emitted with a continuous spectrum of energies. The average energy of the particles is about one-third of the maximum indicated here.

with an equilibrium power similar to that of Sr^{90}—that could be used for this task. This, however, has the additional disadvantage of a very considerable γ-emission, making shielding essential for a crew-carrying ship and complicating the problem of fuel handling. Such a plant might well be used to power an unmanned cargo carrier. In this connection it may be noted that any β-emitter will always have a certain amount of γ-radiation of Bremmstrahlung origin associated with it.

If we suppose that the β-emitting material is deposited at a density of 30 mg./cm.$^{-2}$ on a base of 5 mg./cm.$^{-2}$, while the density of the associated grids, collector plates, busbars and supports is 25 mg./cm.$^{-2}$, we have for the case of the Sr^{90} power plant a total mass of 24 tonnes and an area—for a triple parallel system—of $1{\cdot}3 \times 10^4$ m.^{2}, equivalent to a circle of 65 m. radius. Each emitting plate must dissipate 250 W./m.$^{-2}$—cf., 800 W./m.$^{-2}$ quoted in Fig. 7. If Y^{91} or Ce^{144} is the emitting material the area will be greatly reduced and may in fact be limited by temperature considerations. In any case the contribution of this electric generating system to the over-all specific mass will be small, 2 kg./kW. or less according to the density of deposition, half-life, atomic number, etc.

It will be seen that while this power system is commendably light and simple, the provision of atomic fuel for it, even considering only a very modest fleet of ships, will require a vast atomic energy programme and will, of course, be extremely expensive, while handling of the fuel will be a major deterrent. Acting on the sometimes questionable theory that the best things in life are free, we will now turn our attention to the utilization of solar power.

* *This table is taken from "Nucleonics," May, 1951, with slight omissions.*

Solar Thermopile Power System

A simple way of converting solar radiation to electric power is by the use of thermocouples. This method does not involve the use of high temperatures or moving parts. There have been a number of attempts at power conversion by this means, most of them for small power outputs at efficiencies of 1 per cent. or less. Recently, however, efficiencies up to 7 per cent. have been achieved.[10]

Among the properties of an efficient thermopile it may in general be stated that it will consist of a number of identical thermocouples, each having its two components of the same length and with constant cross-sections such that equal amounts of heat are conducted away by the two components; the external load will be nearly equal to the internal resistance; lateral thermal conduction between thermocouples, together with the smallness of the effect, will enable the Thompson effect to be neglected. Ideally, the thermo-elements should have a low specific electrical resistance (ρ) and a low specific thermal conductivity (k). For metals and alloys these quantities are related by the Wiedemann–Franz law ($k\rho = 2{\cdot}45 \times 10^{-8}T$), all known deviations being in the unfavourable direction. Where this law holds we may give the efficiency of the thermopile to a first approximation by:

$$\eta = \frac{e^2 (T_h - T_c)}{2T_h e^2 + 2 \times 10^{-7}(T_h + T_c)}$$

where T_h and T_c are the absolute temperatures of the hot and cold junctions respectively, and where the open circuit voltage is given by $E = e(T_h - T_c)$. This expression for the efficiency has shown good agreement with experiment for $T_c = 300°$ K. with T_h having values up to 700° K. and with η having values up to 5·6 per cent.[11] Efficiencies at this relatively high level are obtained from intermetallic compounds with small amounts of added metal "impurity" serving to diminish specific resistances. It is unfortunate that a majority of the metals providing high thermoelectric powers (Sb, Bi, Se, Te, Si) have comparatively low melting-points and cannot be employed at high temperatures. A thermocouple consisting of a semi-conductor (PbS) against a ZnSb alloy has provided an efficiency of 7 per cent.,[10] the deviation from the expected 10 per cent. being ascribed to the imperfection of the electrical connection to the PbS. It seems probable that high efficiencies, especially in the temperature range 1,000° to 350° C., will be obtained only by the development of semi-conductor–metallic or semi-conductor–semi-conductor thermocouples. The very wide variation in efficiency of such thermocouples that is consequent upon minute changes of impurity concentration suggests that a profitable field of research may lie in this direction.

It will be noticed that the expression for the efficiency of a thermopile does not include the linear dimensions of the thermoelements. It follows, therefore, that their dimensions may be reduced (while the approximations implicit in the equations hold) until limitations in the heat transfer to and from the hot and cold junctions occur. For the rather inefficient case of heat transfer from a hot gas with a temperature differential of 107° C., Geiling[11]

deduces a mass of 40 kg. per absorbed kW. for a specific thermopile under consideration; this is some two orders of magnitude higher than can be tolerated for the present purpose. Before considering the degree to which this figure can be reduced, it will be useful to outline the form which a solar thermo-generator will take.

One unit, having an area *circa* 100 m.², of a solar thermopile power system is shown in Fig. 6, the position of adjacent units being indicated by dotted

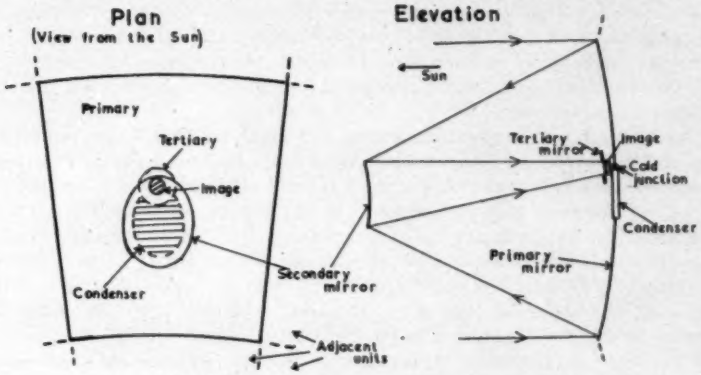

FIG. 6. Solar thermopile power unit.

lines. It is assumed that the mirrors will reflect at 95 per cent. efficiency and that the condenser emissivity is 0·95. The double mirror system serves to shield the condenser from the Sun's radiation and allows the main supporting structure and busbars to be placed on the shadowed side of the primary mirror. The required solid angle of the primary mirror is dependent on the allowable back radiation from the hot junctions and on the position of the secondary mirror. This position in turn determines the amount of incident radiation that the secondary intercepts. Considering these and other factors the compromise used here employs a mean 55° angle—at its focus—for the primary mirror with the secondary intercepting 6 per cent. of the incident radiation. This gives 10 per cent. back radiation with the hot junction of the thermopile at a temperature of 1,000° C. The mirrors are aspherical and are assumed to be a few microns of silver deposited on a 0·001-cm. thick duralumin base. The image is offset as shown so that it appears at one edge of the condenser area. The condenser radiates both ways, the sunward side being in the shadow of the secondary mirror. It has an emitting area of 0·13 m.² per absorbed kW., which compares with the 2·2 m.² per absorbed kW. of the primary mirror, this being capable of delivering full power at 1·6 Earth radii from the Sun. Closer approaches are automatically compensated since the image size increases appropriately and the correct wasting reflection takes place from the tertiary mirror round the thermocouples. The radiating temperature of the condenser is 330° C., the 50° C. difference between this temperature and that of the cold

junctions resulting in the condensation of a liquid evaporated by the cold junctions. This liquid is returned to the cold junctions from the condenser walls by the 4 to 8 cm./sec.$^{-2}$ acceleration imparted to the condenser by the rotation of the entire power system, the offset image being on the "down" side of the condenser. The thickness of the condenser walls must be such that they are reasonably meteor-proof,[12] and they have been put at 0·006 cm. (Meteor "bumpers" cannot, of course, be used in this case—unless they are transparent well into the infra-red.) The total area of a system delivering 10,000 kW. at 5 per cent. conversion of absorbed power is 450,000 m.^{2} Assuming this to be in the form of a disc with a central hole—so that the centrifugal force shall not vary excessively—of 200 m. radius, this requires an outer radius of 425 m., while a revolution every seven minutes will give the required centrifugal force.

The hot and cold junction temperatures of 1,000° and 380° C. are tentatively presented as convenient values taking into account the various factors involved. It is a *sine qua non* that the bulk of the incident heat energy should be absorbed by the hot junction, that part which does not appear as electric energy being transferred to the cold junction. This means that the incoming radiation must have an equilibrium temperature much higher than the hot junction temperature. If the latter is high the mirror must embrace an inconveniently high solid angle in order that the former may be higher still. It should also be borne in mind that the number of thermocouple materials that can be used becomes more limited as the temperature is raised. Any specific temperature used will be designed to suit the thermocouple rather than vice versa, although the thermocouple must be such that the order of magnitude of the temperature is correct; this is owing to the high value of the minimum temperature that is available to the cold junction.

The cold junction temperature has its lower limit set by the ability of the condenser system to abstract heat from it and then radiate the heat into space, such a condensing system being necessary in any power plant having local evolution of heat which cannot be carried away by the exhaust stream. At the temperatures involved it is a simple matter to obtain radiating surfaces with an emissivity (ϵ) of the order of 0·95. Fig. 7 shows temperature against radiating area for this value of ϵ and a power dissipation of 1 kW. (The solar constant is about 1·5 kW./m.$^{-2}$ at the Earth's orbit.) Remembering that the condenser system will be of comparatively massive construction, the advantages of a high temperature and small radiating area are manifest. The radiating temperature finally adopted will be a function of the mass and the temperature–efficiency relation of the remaining parts of the power system. A temperature of 330° C. results from the dimensions given in the present illustrative case. This leaves a 50° C. temperature differential for the transfer of heat from the cold junctions to the radiating surfaces. It seems probable that no system can make this transfer with greater economy of mass than that involving the evaporation of liquid from the cold junction followed by its condensation on the radiating walls and its return to the cold junctions. Hydrocarbons, silicones, mercury and other low melting-point metals are some of the substances that might be considered for this purpose.

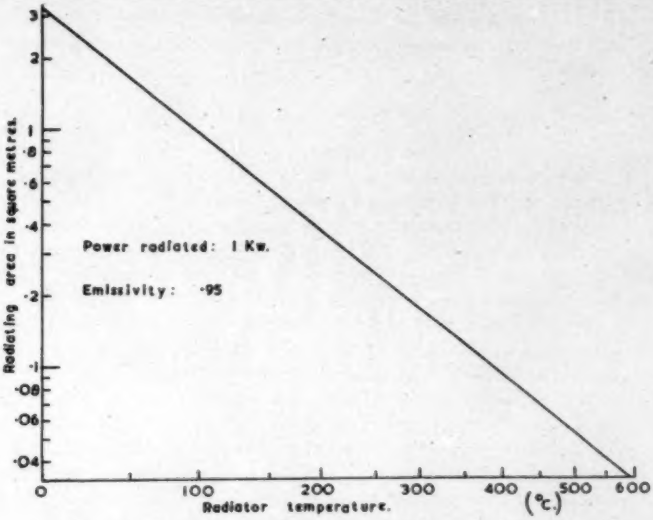

FIG. 7. Radiator temperature as a function of surface area.

In this connection it is worthwhile noting that, in mercury cycle power generators, on the addition of certain substances to the mercury, a mercury film forms on the boiler tubes. This film has a high surface tension which allows it to be heated to a temperature in excess of the saturated vapour equilibrium temperature and it is renewed by a vapour-liquid "fog" of about one-twentieth of the density of the liquid alone.[13,14] Such a system has the advantages of requiring a low mass of coolant and of having a heat transfer coefficient (defined by $P = \alpha ST$, where P is power in watts, S is the interface area in cm.^{2} and T is the temperature differential in ° C.) approaching unity. While for the temperature postulated mercury would have too high a vapour pressure to be used as the coolant, it is possible that other metals could be used[15] or that the radiating area could be doubled, with consequent increase in mass, and mercury used at 230° C. and 4 cm. of Hg pressure. A forced feed system might be used to maintain a high heat transfer coefficient, but the acceptance of a reduced value of this would probably be preferable.

The mass of the mirror and condenser system is assumed to be of the order of 120 g. per absorbed kW., 75 per cent. of the incident radiation being absorbed at the Mars orbit. The mirror is of extremely light construction since small deformations and meteor punctures do not affect its performance. The condensing system having 1/30 of the area of the mirror system has about twice its mass. This is owing to its comparatively heavy walls, its internal subdivisions that serve to limit meteor damage and the condenser liquid. Allowance for supporting struts and ties has been included in the over-all figure. At 5 per cent. conversion efficiency this accounts for 2·5 kg./kW. of the thermal–electric specific mass.

We will now consider the mass and efficiency of the thermocouples themselves. If 10 per cent. back radiation takes place at the hot junctions we have the relationship:

$$10A\epsilon\sigma T_h^4 = ak(T_h - T_c)/L \quad \text{or} \quad \frac{0{\cdot}24L}{k} = \frac{a}{A}$$

where A is the image size, a is the total cross-section of the thermocouples, L is their length and k is their mean thermal conductivity. A is fixed by the operating position of the ship and k by the characteristics of the thermocouples. If a is approximately equal to A no heat transfer problem arises since the hot junctions receive the radiation directly. L is then defined by the above equation and, depending on k, will be of the order of 1 cm. or less. Since the image area is of the order of 6·5 cm.^{2} per absorbed kW., this results in a thermocouple mass of the order of 60 g. per absorbed kW. or less. Further considerations, particularly heat removal at the cold junctions, may make the identity of $a = A$ undesirable. If $a > A$ the image will be thrown into a hollow cone of base area A and wall area a. If $a < A$ the thermocouples will be provided with conducting "heads" to increase the amount of radiation they receive. As an illustrative case for the cold junctions we will take the optimistic value of 0·5 for the heat transfer coefficient, a temperature differential of 50° C. and a finning of the junctions to provide an effective transfer area of $5a$. We then get a cross-section of 8 cm.^{2} per absorbed kW. These figures suggest that the mass of the thermoelements per absorbed kW. (M) will be of the order of 100 g. Fig. 8 shows the over-all specific mass against M for various conversion efficiencies where the efficiency is the conversion efficiency from absorbed heat energy to delivered electric energy; the mirror–condenser mass is 120 g. per absorbed kW.; the ion gun conversion efficiency is 70 per cent.; the ion gun has $\frac{1}{2}$ kW./kg. specific mass; specific masses shown are in terms of momentum in the exhaust beam.

From a consideration of the foregoing and Fig. 8 we may conclude that a solar thermopile power system may reasonably be expected to deliver power at over-all specific masses of the order of 10 kg./kW. or less, with the possibility of further improvement resulting from the synthesis of more suitable semiconductors and advances in the constructional and mechanical engineering fields concerned.

Indirect Atomic and Solar Power Systems

The use of heat energy–mechanical energy–electric energy sequences is not superficially so attractive as the direct systems we have discussed. They introduce moving parts, condenser systems more massive than those so far discussed and mechanical electric generators. It may fairly be assumed, however, that heat-powered turbines may be designed in terms of standard practice to deliver mechanical energy at an acceptable specific mass—say 2 kg./kW.—while the provision of a suitable electrostatic generator has already been discussed. With a solar energy power source a system of single mirrors would supply an appropriate radiation density to boiler tubes which would

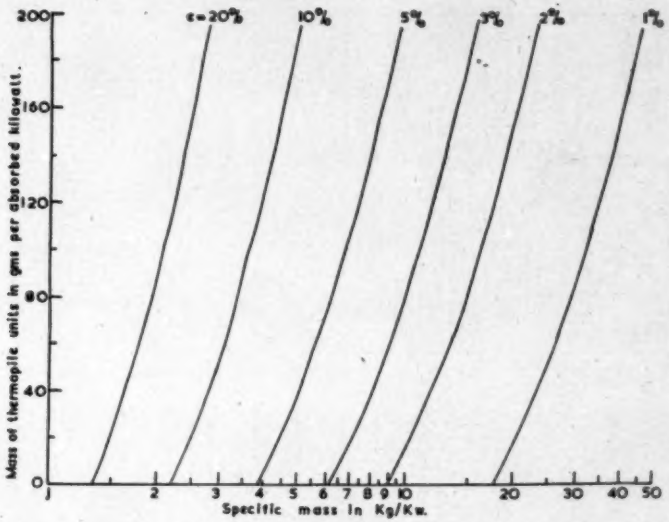

FIG. 8. Specific mass as a function of thermopile mass and efficiency where mass of mirror-condenser system is 120 g./absorbed kW.; electric power is converted to exhaust power at 70 per cent. efficiency; the specific mass of the ion gun system $\frac{1}{4}$ kg./kW. of delivered power: absorbed heat is converted to electric power at the efficiencies (ϵ) shown.

deliver high pressure gas through turbines to a condenser system similar in principle to that described above, the working fluid or a secondary fluid being used to carry heat to the radiators. The condensing temperature will, as has been indicated, be high, and mercury might be used as a suitable working fluid. It seems unlikely that such systems will be able to provide a lower specific mass than could be obtained with a thermopile generator.

The use of an atomic indirect system, in which a pile provides the heat energy, deserves more attention, however. At about the orbit of Jupiter, or perhaps even closer to the Sun, the use of mirrors to collect solar radiation on a sufficient scale will become impracticable owing to the size and mass of the mirrors that would be required, and reliance will have to be placed on atomic power. The fuel for the elegant β-emitter method will be extremely expensive and limited in quantity, while a pile power source is relatively cheap (and no idling loss occurs). Such a system brings with it the radiation and other problems that are so well known in one or two laboratories to-day, and since in this case a low mass will be necessary some of these will appear in aggravated form. There is little doubt that a solution to such problems can be found, however, though probably at the cost of a fairly high specific mass. For several reasons a pile heating thermocouples is not at all likely to be a satisfactory system.

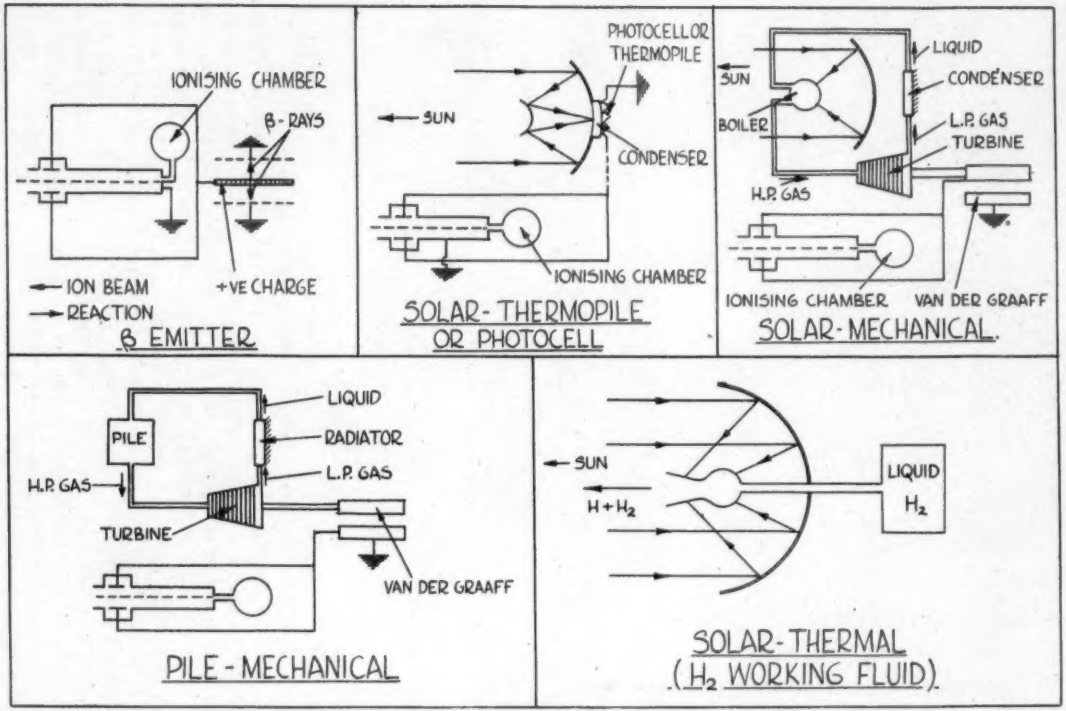

FIG. 9. Diagrammatic sketches of various drive systems considered.

Applicability of the Design Formulae

The design formulae represented in Figs. 1, 2, 3 and 4 hold accurately only for the case of optimum power/fuel mass-ratios and for specific masses that are independent of power plant size. The optimum power plant/fuel mass-ratio will be employed only if the cost of neither the fuel nor the power plant is very greatly in excess of the other. Thus the expense of a β-emitter would result in a reduction of power plant mass from the optimum value in its case, while the requirement that the fuel supply for a series of journeys for a solar-powered ship should be transported from Earth would result in its being over-powered in comparison with the optimum value.

In solar and β-emitter power plants efficiency may reasonably be supposed to be independent of size, but in a plant that includes an atomic pile this will not be so, since in this case efficiency will increase with size, at least until some definite size has been reached. One of several reasons for this is that the mass of the radiation shields will not increase proportionately with the power.

The main losses in the ion gun system may be expected to occur in the ionizing process, and since for a given power output the ion current density changes with changing exhaust velocity, it is not to be supposed that the ion gun efficiency, and hence the specific mass, will in fact be independent of the exhaust velocity. Certain considerations suggest, however, that this variation will be a minor one. In the first place, if the gun is operating at a high efficiency, a given percentage variation in ionizing power requirement will have a much smaller percentage effect on the specific mass. For instance, for the 70 per cent. efficiency postulated earlier a 5 per cent. change in ionizing power will result in only 2·1 per cent. change in specific mass. With every improvement in design—higher efficiencies, higher accelerating voltages—this effect will become more marked. As an instance of possible improvement, the illustrative figures given imply an ionizing power consumption of 90 W./mA.; and while the ionization is under less favourable conditions than those found in standard practice—ionization of particles instead of molecules—the comparison with values of the order of 1 W./mA. that have been obtained suggests that there is a possibility of this estimate being pessimistic. If the exhaust velocity goes up and the ion current falls, while the accelerating voltage is held constant, either the charge on each particle must increase or the particle size must decrease. Both these conditions may be supposed to decrease the ionizing efficiency, partially compensating thereby the decrease in losses resulting from the smaller beam current. For the above reasons it seems reasonable to suppose that the application of formulae implying the independence of exhaust velocity and ion gun efficiency will be accurate to a first approximation.

Although our formulae may break down for pile-operated ships on physical grounds and for β-emitters on economic ones, it appears that for all forms of solar-powered ships they will hold fairly accurately. This is fortunate since, in the writer's opinion, these are the class that show most promise of providing economically practicable transport.

Further Transport Considerations

We have so far suggested figures that would be tolerable for a crew-carrying ship. If we are concerned with the bulk transport of fuel or raw materials,

however, we may contemplate with equanimity transport by auto-directed ships with transit times up to ten years or so in length. Such an extension will enable great reductions in fuel and/or power capacity to be made. It should be emphasized, however, that an atomic plant does not commend itself for these systems, as however slowly the transfer takes place the high *total* power requirements—increasing with decreasing fuel mass—demand high atomic fuel consumption, always a major source of expense and generally a major difficulty of supply. For a solar-powered system, on the other hand, increased total power demands can be met simply by an increase in time; if we can afford to decrease our acceleration we can increase our characteristic velocity and/or our mass correspondingly without affecting our fuel situation. As an example, a solar-powered ship with a total mass of 5,000 tonnes, a specific mass of 4 kg./kW., a fuel + power plant mass of 1,500 tonnes, a fuel mass of 800 tonnes, an exhaust power output of 35,000 kW. and an exhaust velocity of 100 km./sec. will reach Earth from the asteroid belt (requiring a characteristic velocity of about 17 km./sec. for this time) in approximately three years. In this way, besides the delivery of cargoes to Earth, fuel for the faster manned ships may be brought to any convenient location, eliminating the necessity for carrying amounts of fuel sufficient for "round trip" voyages. This will materially increase the accelerations and payloads available to such ships.

The advantages arising from a ground station, situated on a satellite or in space, which is capable of applying a high (10 *g*) or very high (100 *g*) acceleration to a mass of the order of a few tonnes has been dealt with previously[1]; a few remarks may be added, however. In addition to the electromagnetic drive postulated, a piston driven by compressed gas or by a rocket motor that exhausts into a cylinder may be used. If such a rocket uses, say, hydrogen and oxygen as fuels, recompression, electrolytic dissociation and liquefaction may take place at leisure, using solar-derived power, after the launching. This is less neat than the electromagnetic method, which seems preferable to the writer, but it does effectively overcome the difficulty of energy storage.

Velocity may be imparted but cannot be checked—except by impact, which is destructive—by such ground stations. It is possible, however, for atmospheric braking to occur. Where relative velocity is considerably above escape velocity this will require so high a velocity destruction on the first passage through the atmosphere that it will be difficult to design a shuttle that at once prevents its occupants being roasted and which allows control to be maintained. Heating will not be so serious a problem with unmanned shuttles. If it is not desired to land on the grazed planet a further application of power must, of course, be made—unless the velocity is still above escape velocity. It is assumed that all cargoes will be delivered to Earth using only atmospheric braking in their final stage, rocket braking being inadmissably expensive. It may, however, be economically justifiable to utilize the high acceleration inherent in chemical rockets for the selective transfer of personnel between various points of the planetary and solar systems. Ships with transit times greater than about a year will presumably never carry a crew.

We thus envisage a system in which fuel and cargoes are derived from

satellites and asteroids. The crew of the original ship, which will be brought from Earth and assembled in a satellite orbit, will build the necessary heavy equipment, stations and ships, originally at Deimos and later from material from any of the low-gravity bodies of the inner solar system. The raw materials which will be delivered to Earth as a result of this project will to a large extent offset and justify the initial capital costs, and will finance the expansion of the project and also the purely scientific expeditions which will then proceed to explore the outer solar system and to descend to the surface of the inner planets.

It is perhaps worthy of note that most sections of the operating plants described in this paper can be accurately simulated in a laboratory, and where this is not possible, as in the case of constructing stress-free frameworks, the problem is susceptible of accurate mathematical analysis. For these reasons the experimental work required to develop such power plants could be undertaken on Earth at a cost that might be estimated to be between one and ten million dollars, the latter figure being the more probable one. Such experiment would, of course, be pointless unless the establishment of a satellite station was envisaged. This would involve an expenditure of the order of a thousand times the former figure.

The writer is indebted to Dr. L. R. Shepherd for some very helpful discussions during the preparation of this paper.

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ADDITIONS TO LENDING LIBRARY

The following books have been added to the Society's Lending Library and are available to Fellows resident in Great Britain holding library tickets.

The Artificial Satellite. Edited by L. J. Carter (1952).
Das Marsprojekt, by Wernher von Braun (1952).
Die Rakete zur Höhenforschung, by V. Mandl (1934).
Out of the Sky, by H. H. Nininger (1952).

FIRST INTO SPACE

On September 19, 1783, before Louis XVI and the Court of France at Versailles, a sheep, a cock and a duck were sent into the air in a Montgolfier hot-air balloon, and so the honour of being the first aerial passengers went, not to any representatives of our species, but to some of what we are pleased to call "the lower animals." (It is chastening to reflect that there is, of course, no record of what *they* call *us*.)

History repeated itself recently, when a party of mice and monkeys became the first rocket crew on record to fly into space beyond the atmosphere; only last November, Dr. Schaeffer (of the U.S. Naval School of Aviation Medicine) predicted that the passengers on the first lunar trip would probably be dogs or cats, sent to check the safety of the mission before Man dared to follow their example, and it looks as though he may well be right. One feels that our little furry friends should be given full credit for their pioneering work, even if (like Nelson's sailors) they were press-ganged into the adventure. Of course, carping critics may protest that the rocket flights so far made have not really penetrated into space itself, but that introduces the difficult question of where "space" should be defined as beginning—since of course the Earth's atmosphere does not end abruptly, but tapers off very gradually into the near-vacuum of interplanetary space. Even the latter is not strictly a vacuum—a few lonely gas molecules and dust particles exist in the interstellar void, to say nothing of meteors and other larger hazards to astronavigation.

In its April issue *Aeronautics* speculated on these matters, pointing out that the Douglas "Skyrocket," in its flights to altitudes of about 15 miles, had already carried men to "the fringe of space," while other American research "aircraft" (such as the X-2 and the X-3) would soon go higher still; their editorial, incidentally, concluded with the expression of some sentiments with which we can wholeheartedly associate the B.I.S.: "The aeroplane will merge, by a process of change and development, into the 'spaceship.' But it would be as well if we in this country were more active in the development of craft capable of undergoing this metamorphosis and of turning themselves into spaceships capable of attaining extreme altitudes. It is one of the serious omissions of our research programme that, in this field, we have nothing comparable with the American machines."

However, the intrepid mice and monkeys referred to earlier appear to have travelled much further into space than Bridgeman in his "Skyrocket." Early conflicting reports made it difficult for us in this country to discover exactly what had been done, but a clearer picture seems to have emerged now.

In the recent excellent space-flight feature in the American magazine *Collier's* Willy Ley mentioned the fruit flies sent up in a V.2 a few years ago, and said: "It seems reasonable to assume that larger creatures have been rocketed past the atmosphere since then." The *Collier's* issue appeared on March 22, and was put together by their associate editor, Mr. Cornelius Ryan; speaking to the Canadian Club in Toronto about about this time, Mr. Ryan claimed that monkeys had been shot at least 25 miles high in V.2 rockets.

According to some reports, he added that the information had not been publicly released because of the anticipated reactions of animal lovers!

Be this as it may, within a few days an official statement was forthcoming from the U.S. Air Force. Dr. J. P. Henry, of the Wright Field Aero-Medical Laboratory, revealed that a number of tests had been made. Together with his colleague, Dr. E. R. Ballinger, he described the results to the Aero-Medical Association's annual meeting in Washington, D.C., and in subsequent interviews.

Apparently, a number of Rhesus monkeys and some mice have, on a number of occasions, been sent some 80 miles high in V.2 rockets fired from White Sands. The monkeys were anaesthetised before take-off, and rode in pressurised capsules 3 feet long by 15 inches diameter, strapped down by nylon netting on sponge rubber beds. It was the intention to land the capsules safely by parachute, but the arrangements failed to work satisfactorily on all except one occasion, so that four monkeys were killed. Even on the single occasion when a fifth monkey was safely landed, it died from heat stroke in the desert before it could be picked up. However, complicated telemetering equipment had been provided to transmit information on the monkey's blood pressure, pulse and respiration rates, etc., and this showed that they had suffered no ill-effects during the actual rocket flight.

On other occasions, a number of mice (two to ten at a time) were sent up to altitudes of about 40 miles in Aerobee rockets. The landing parachutes for the capsules worked in these tests, so that the mice survived. They are now still breeding freely, having suffered no ill-effects from cosmic radiation on their reproductive mechanisms. Of course, the Aerobee ascents would have lasted only some 10 minutes, so that this evidence is not conclusive. Of greater interest is the fact that, for some three minutes or so, the mice were substantially weightless, but "suffered no immediate disturbances" and did not lose their powers of co-ordination. A small camera in the capsule was used to film the mice, which (to quote Dr. Henry) ". . . were as much at ease when inverted as when upright . . . they merely lost the vertical reference of gravity and assumed whatever posture was convenient." One mouse, with the balance mechanism of its inner ear destroyed beforehand, is said to have remained curled up in a corner of the capsule, unaware that it had become weightless! Dr. Henry said that he believed pilots would have "no difficulty in performing all actions necessary to control an aircraft" while in a weightless state.

The newspapers all over the world made much of the above statements, with comments that displayed an almost universal intense interest and a varying degree of amusement. As for the latter, we are reproducing here two of the better of the many cartoons, etc., which appeared in British papers! The *New York Herald Tribune*, in its Paris edition, looked forward to the day when one of the returned space voyagers would ask a more timid fellow-rodent whether he was a mouse or a man, and *The East Anglian Daily Times* expected to see a Sunday newspaper article on "Forty Miles Above the Earth: What it Feels Like—by a Mouse Who Knows."

There should, of course, be no doubt that such experiments as these are of real scientific value and deserve to be taken seriously. We have heard

"Capt. Frisbee, meet our Chief Test Pilot."

"You were right, Captain—it *is* green cheese!"

The cartoon (left) is reproduced by courtesy of the Editor of the *Sunday Chronicle*, and (right) by courtesy of the Editor of the *News Chronicle*.

it suggested that the rockets used could have been better employed in carrying cosmic ray instruments or apparatus to secure other physical data, but anyone who hopes to see manned rocket flights in the near future could hardly begrudge some effort being expended on the physiological problems involved. Quite apart from the purely medical aspect, the psychological and publicity value of securing definite proof that high animal organisms can survive high altitude rocket flight is not to be overlooked.

One of the less understandable British reactions to the news of the experiments was a fatuous protest from the R.S.P.C.A.—a body from which we would have expected a more enlightened attitude—suggesting that the tests were a parallel to some of the things done during the war in Nazi prison camps. Conceding that experiments on animals might be justified if likely to lead to the cure of human diseases, the R.S.P.C.A. also admitted that a similar "defence" might be made of tests on "offensive weapons for the defence of civilisation"(!!!), but they were unable to see that work leading to human rocket flight justified such means.

NOTES AND NEWS

A.R.S. Journal

A recent circular to Fellows of the Society pointed out that supplies of the greatly enlarged *A.R.S. Journal* are very limited, and in view of this it has been decided that copies will be distributed in future only to those Fellows who specifically request them.

It is realised that the previous system of distribution in rotation involved considerable waste, as the *A.R.S. Journal* is now a highly technical publication devoted almost exclusively to rocket engineering, and the interests of many

of our Fellows lie in other fields. Moreover, many of those concerned with rockets already receive copies from other sources.

The contents of each journal, as received, are noted in the Abstracts section of the *B.I.S. Journal*, and an almost complete file of back numbers is maintained for those who wish to refer to specific articles. Requests for the loan of individual issues should be sent to J. Humphries, 97, Churchill Avenue, Southcourt, Aylesbury, Bucks.

The Third International Congress on Astronautics

The G.f.W. intend to arrange a rocket exhibition to be held in conjunction with the Third International Congress on Astronautics at Stuttgart, September 1-6, 1952, and have asked for assistance from B.I.S. members with suitable exhibits, e.g. models, photographs, drawings, etc.

Such exhibits may be sent beforehand direct to the G.f.W., at Langobardenstrasse, 15, Stuttgart-Zuffenhausen, Germany, or brought personally by intending participants at the Congress.

B.I.S. members who will definitely be attending are reminded that they should advise the Secretary as soon as possible in order that lists can be prepared. Details of the arrangements made for the B.I.S. party will be circulated to those listed in due course.

Observations of the Moon at Paris Observatory

Two Fellows of the Society, H. Percy Wilkins, F.R.A.S., and P. A. Moore, F.R.A.S., recently visited Meudon, where the giant telescope of the Paris Observatory (the third largest refractor in the world, objective 33 inches, focal length 52 feet) was placed at their disposal for the purpose of lunar observations, through the courtesy of the Director.

Although bad weather curtailed the programme, much interesting information was obtained, including minutely detailed charts of Plato, Guerické and Riccioli.

Contrary to what most textbooks affirm, the view of the Moon through this giant instrument was vastly superior to anything seen through smaller telescopes. Some objects, which in smaller telescopes appeared comparatively smooth with but few surface wrinkles were revealed as being literally covered with a mass of mounds, ridges, cracks, pits and craterlets down to a few hundred feet across, clearly demonstrating how rough and uneven the lunar surface really is. Some remarkable and indeed hitherto unthought of types of objects were revealed!

The classification and charting of the features discovered will take some considerable time, but it is clear that these areas of the Moon will soon be known with an accuracy approaching that of ordinary terrestrial maps.

The Armstrong-Siddeley "Snarler" Rocket Motor

Mr. K. W. Gatland has pointed out that the "Snarler" was fitted into the prototype P.1040 (which was then redesignated P.1072) and not into the N7/46, which is the naval version of the land fighter, and which, as such, has never gone into production.

It is also of interest to mention that Mr. A. E. Dixon, another member of the Society, did much of the stress work for the installation in the airframe.

Interplanetary Play

Last December, the little New Chepstow Theatre put on a play about space travel—"6,000 Years to Sirius," by Peter Tremlett—which can perhaps best be described as a very brave try. At any rate, it gave some indication of the potential dangers of space-flight, for the author (who also produced and played the lead) was injured by electrocution on the set just before the originally-planned opening night. He had been adjusting some of the ingenious effects (worked by the "controls" in the space-ship's cabin), but recovered in time for the postponed first performance to take place two days later.

ABSTRACTS

Edited by J. HUMPHRIES

Abbreviations of titles of journals were given in the May, 1950, issue of the *Journal*, and addenda have appeared in subsequent issues. The following is a further addendum to the list:—

Ann. Télécomm.	Annales de Télécommunication.
Calif. Engr.	California Engineer.
J. Heredity.	Journal of Heredity.
Proc. Instn. Mech. Engrs.	Proceedings of the Institution of Mechanical Engineers.

Many of the articles noted are available on loan to members resident in the British Isles. Requests should be addressed to J. Humphries, 97, Churchill Avenue, Southcourt, Aylesbury, Bucks.

AERODYNAMICS

(167) **Laminar friction and heat transfer at Mach numbers from 1 to 10.** E. B. KLUNKER and F. E. MCLEAN. *N.A.C.A. Tech. Note No.* 2499 (*Oct.*, 1951).

AIRCRAFT

(See also Abs. No. 239)

(168) **A method of selecting rocket thrust for experimental supersonic airplanes.** R. W. BYRNE. *N.A.C.A. Restricted Bull. No. L6G22*, 11 pp. (*Aug.*, 1946).

(169) **Pilotless aircraft research.** W. A. SHRADER. *Aero. Engng. Rev.*, **10** (10), 24-29 (*Oct.*, 1951).
N.A.C.A. programme at Wallops Island where basic aerodynamic data at supersonic speeds is sought. Rocket boosters used to reach speeds up to 2,500 m.p.h. and altitudes of 100,000 feet. Description of telemetering methods and reduction of data.

(170) **Northrop rocket wing.** *Weltraumfahrt* (6), 132-133 (*Dec.*, 1951) (*In German.*)
Description of the first American rocket aircraft.

(171) **The future evolution of the bomber.** E. SÄNGER. *Inter Avia*, **7**, 139-143 (*March*, 1952).
Includes rocket bombers.

ASTRONAUTICS

(172) **Fundamental dynamics of reaction-powered space vehicles.** L. N. THOMPSON. *Proc. Instn. Mech. Engrs.*, **164**, 264-280 (1951).
[See Abs. No. 7, *J.B.I.S.*, **11**, 47 (*Jan.*, 1952)].

(173) **The world of the rocket.** H. GARTMANN. *Westermanns Monatshefte* (*March*, 1951). (*In German.*)
Rocket flight technique and space-flight.

(174) **Preview of space flight.** L. S. BLACK. *Aero Dig.*, **63** (4), 17-24 (*Oct.*, 1951).
General review of problems and possibilities of space flight, including artificial satellites.

(175) **The brainwork is done.** R. McLaren. *Aero Dig.*, **63** (4), 34, 36, 38, 42, 44, 46, 50, 52, 54, 56, 58, 60, 63-64 (*Oct.*, 1951).
Review of the basic theory involved in escape from the earth and consideration of the present status of rocket motors.

(176) **Evolution of the orbital base.** L. Levenson. *Calif. Engr.*, **30** (2), 8-9, 18, 20, (*Nov.*, 1951).

(177) **The foundation of the space-station.** G. von Pirquet. *Linzer Sternenbote*, **5**, 109-115 (*Nov.-Dec.*, 1951) (*In German.*)
Complete text of paper delivered at Second International Congress on Astronautics, London. Sept, 1951.
[For summary see *J.B.I.S.*, **10**, 303 (*Nov.*, 1951).]

(178) **The satellite station as a gyroscope.** W. Schaub. *Weltraumfahrt* (6). 121-125 (*Dec.*, 1951). (*In German.*)
Consideration of the various conditions under which a satellite station can precess.

(179) **International Astronautics Federation.** E. V. Sawyer. *Pacif. Rocket Soc. Bull.*, **5** (1), B1-B4 (*10th Jan.*, 1952).
The P.R.S. representatives' view of the proceedings at the Second International Congress on Astronautics.

(180) **An instrument for determining the deceleration firing point.** M. Conley *J. Space Flight*, **4** (2), 4-5 (*Feb.*, 1952).

(181) **The cost of interplanetary cargo transportation. Pt. I.** N. J. Bowman. *J. Space Flight*, **4** (3), 1-10 (*March*, 1952).

(182) **Artificial satellites—key to space flight?** L. N. Thompson. *Inter Avia*, **7**, 148-150 (*March*, 1952).
Elementary considerations of space-flight and sub-orbital satellite techniques.

(183) **Crossing the last frontier.** W. von Braun. *Collier's*, 24-29, 72, 74 (*22nd March*, 1952).
The stages in setting up a manned space station.

(184) **A station in space.** W. Ley. *Collier's*, 30-31 (*22nd March*, 1952).
Impression of manned space station.

(185) **Who owns the universe?** O. Schachter. *Collier's*, 36, 70-71 (*22nd March*, 1952).
Legal problems in space and on other bodies.

(186) **The heavens open.** F. L. Whipple. *Collier's*, 32-33 (*22nd March*, 1952).
The use of space vehicles for astronomical research.

(187) **Interplanetary travel between satellite orbits.** L. Spitzer. *J. Amer. Rocket Soc.*, **22**, 92-96 (*March-April*, 1952).
Reprinted from *J.B.I.S.*, **10**, 249-257 (*Nov.*, 1951).

(188) **Artificial satellites.** J. Humphries. *Aeronautics*, **26**, 62, 65-66, 69-70 (*April*, 1952).
The problems involved in constructing instrument and man-carrying artificial satellites and their uses. Meteor hazards and physiological problems.

ASTRONOMY

(189) **Interplanetary matter.** C. Hoffmeister. *Naturwissenschaften*, **38**, 227-234 (*May*, 1951). (*In German.*)

ATMOSPHERE

(190) **High-altitude research using the V.2 rocket, March, 1946—April, 1947.** L. W. Fraser and E. H. Siegler. *Johns Hopkins Univ., A.P.L., Bumblebee Series, Rept. No.* 81, 90 pp. (*July*, 1948).

(191) **The upper atmosphere.** *Aero Dig.*, **63** (4), 80, 82, 84 86, 88, 90-92, 94, 98, 100, 104-105 (*Oct.*, 1951).
First part deals with the history of research into the atmosphere and the second part is a review of our present-knowledge based mainly on Grimminger's work. (19 refs.)

(192) **This side of infinity.** J. Kaplan. *Collier's*, 34 (*22nd March*, 1952).
Properties of the atmosphere.

BIOLOGY AND MEDICINE

(193) **Physiological endurance and rocket flight.** G. A. Crocco. *Aerotecnica*, **5**, 55-59 (*Feb.*, 1951). (*In Italian.*)
It is shown that because of low human tolerance of acceleration a manned space rocket must have wings and will not take off vertically.

(194) **A study of genetic effects of cosmic radiation on cotton seed.** G. N. Stroman and T. H. Lewis. *J. Heredity*, **42**, 210-213 (*July-Aug.*, 1951).
Tests carried out in V.2. No positive results.

(195) **Life in a free falling body.** L. Levenson. *Calif. Engr.*, **30** (1), 8, 32 (*Oct.*, 1951).

(196) **On the possible nature of extraterrestrial life.** J. England. *J. Space Flight*, **4** (2), 1-3 (*Feb.*, 1952).

(197) **Flight at the borders of space.** H. Haber. *Sci. Amer.*, **186**, 20-23 (*Feb.*, 1952).
The earth's atmosphere and biological and other effects at high altitude.

(198) **Man without gravity.** L. N. Thompson. *Flight*, **61**, 298-300 (*14th March*, 1952).
The physiological and psychological problems of space-flight.

(199) **Can we survive in space?** H. Haber. *Collier's*, 35, 65-67 (*22nd March*, 1952).
Discusses the various physiological phenomena.

CHEMISTRY

(200) **The thermal decomposition of nitromethane.** L. J. Hillenbrand and M. L. Kilpatrick. *J. Chem. Phys.*, **19**, 381 (*March*, 1951).

(201) **Handling hydrogen peroxide.** A. V. Cleaver. *D.H. Gaz.* (67), 20-21 (*Feb.*, 1952).
Discusses the properties of high strength peroxide (80 per cent.), compatible materials and the safety precautions to be observed during handling, including protective clothing.

MATERIALS

(202) **Resistance to thermal shock.** C. M. Cheng. *J. Amer. Rocket Soc.*, **21**, 147-153 (*Nov.*, 1951).
The non-uniform temperature distribution is computed by using the heat conduction equation. This distribution is then used to compute the thermal stress. The parameters used are the coefficients of thermal conductivity and expansion, Young's modulus and Poissons' ratio. These together with the heating conditions then specify the resistance to thermal shock. The theory is verified by comparison with N.A.C.A. test data for ceramics and ceramals.

(203) **Strengths of several steels for rocket chambers subjected to high rates of heating.** R. L. Noland. *J. Amer. Rocket Soc.*, **21**, 154-162 (*Nov.*, 1951).
Presents a summary of the results of a series of tests carried out under conditions comparable to those encountered in solid-propellant rocket motors. These indicate that time at temperature has a definite effect on the high temperature strength characteristics of the steels investigated. Strength properties based on a 15-minute exposure time are conservative when actual exposure times do not exceed 5 seconds.

(204) **Equipment for use with high-strength hydrogen peroxide.** N. S. Davis and J. H. Keefe. *J. Amer. Rocket Soc.*, **22**, 63-69 (*March-April*, 1952).
Results of compatibility tests on various materials are presented. General equipment design considerations and methods of preparing equipment for service are outlined. Examples of pumps, containers, piping, flexible hose, valves and reactors are discussed.

(205) **Resistance to thermal shock.** E. Mayer. *J. Amer. Rocket Soc.*, **22**, 98 (*March-April*, 1952).
Letter commenting on "Resistance to Thermal Shock." C. M. Cheng. *J. Amer. Rocket Soc.*, **21**, 147-153 (*Nov.*, 1951).
(See Abs. No. 202.)

MISCELLANEOUS

(206) **Calculations for spindle-shaped bodies.** U. T. Bödewadt. *Weltraumfahrt* (6), 128-131 (*Dec.*, 1951). (*In German.*)

Simplified formulae for the calculation of surface area, volume and first and second moments of area for hollow and solid bodies.

(207) **R. H. Goddard.** W. BRÜGEL. *Weltraumfahrt* (6), 126-127 (*Dec.*, 1951). (*In German.*)
Biographical notes.

PHYSICS

(208) **Electromagnetic flow meter for rocket research.** L. JAFFE, B. A. COSS and D. R. DAYKIN. *N.A.C.A. Research Memo. E50L12*, 15 pp. (*6th March*, 1951).

(209) **A new method for determining the static temperature of high-velocity gas streams.** J. A. CLARK and W. M. ROHSENOW. *Trans. Amer. Soc. Mech. Engrs.*, **74**, 219-228 (*Feb.*, 1952).
The general problem is discussed and a new theromodynamic method based on flow through an orifice is described with results. (14 refs.)

(210) **Energy from the high atmosphere.** N. C. GERSON. *J. Amer. Rocket Soc.*, **22**, 98-99 (*March-April*, 1952).
Letter showing that in one circuit of the earth at 300 km. altitude a 15 meters diameter vessel at escape velocity could collect 5 watt-hour of energy due to ion neutralisation. At just over 100 km. 10^3 kw. hour could be collected by re-association of atomic oxygen.

PROJECTILES

(See also Abs. No. 239)

(211) **The temperature barrier of high altitude, long distance missiles.** C. A. CROCCO. *Atti Accad. Naz. Lincei* (*R.C.U. Sci. Fis. Mat. Nat.*), **10**, 97-103 (*Feb.*, 1951). (*In Italian.*)

(212) **Project cyclone.** *Reeves Instrument Co.*, 148 pp. (*15th March*, 1951).
Development of computor laboratory and guided missile simulator.

(213) **Performance analysis of a sounding rocket.** V. C. Liu. *Univ. of Michigan, Project M893—Memo. No.* 4, 9 pp. (*Aug.*, 1951).

(214) **Advance man to the Moon.** *Aero. Dig.*, **63** (4), 25-32 (*Oct.*, 1951).
The story of the Viking project. Details of the organisations responsible for its development and use. Lay-out of the missile and its equipment, including cosmic ray, pressure, temperature and various other instruments. Chronological history of the first seven firings.

(215) **Aircraft rockets.** *Inter Avia*, **6**, 552-553 (*Oct.*, 1951).
Unguided solid and guided liquid propellant missiles with tabulated data.

(216) **Guided anti-aircraft missiles.** *Inter Avia*, **6**, 554-555 (*Oct.*, 1951).
Basic guidance systems and short descriptions of the more important weapons.

(217) **Rocket away!** *Inter Avia*, **6**, 556-557 (*Oct.*, 1951).
Brief description of the Viking.

(218) **Slingshots or precision weapons?** *Inter Avia*, **6**, 541-547 (*Oct.*, 1951).
Review of Oerlikon aircraft and anti-aircraft weapons, including rockets. Deals with solid propellant types, launching racks and projectors and the liquid propellant guided anti-aircraft weapon.

(219) **The "Wasserfall" remote-controlled A/A missile.** R. H. REICHEL. *Inter Avia*, **6**, 569-574 (*Oct.*, 1951).
The initial requirements of Wasserfall are stated and the development and final version described. Experimental aerodynamic data and method of control are discussed. The propellants and injector types experimented with are given in detail.

(220) **The Viking rocket.** W. G. PURDY. *Aero Engng. Rev.*, **11**, 16-20 (*Jan.*, 1952).
Design considerations and results of flight tests.

RADIO AND ELECTRONICS

(221) **Ionisation in the incandescent gas of a jet propulsion device.** C. KLEIN. *Ann. Télécommun.*, **6**, 287-298 (*Oct.*, 1951). (*In French.*)
Flame ionisation in rocket jets and its effects on radio propagation in the vicinity of the rocket.

(222) **Circuit stability in guided missiles.** R. L. KELLY. *Electronics*, **25** (3), 133-135 (*March*, 1952).

Avoidance of erratic performance by control of grid emission, variation in contact potential, heater-cathode leakage and shock and vibration.

(223) **Simultaneous A.-M. and F.-M. in rocket telemetering.** W. C. MOORE. *Electronics*, **25** (3), 102-105 (*March*, 1952).

Use of two channels on a single carrier, one being a video channel 5 megacycles wide. Details of transmitter designed for Aerobee are given.

ROCKET MOTORS

(See also Abs. No. 204, 208)

(224) **Chemical kinetics and rocket nozzle design.** F. J. KRIEGER. *The Rand Corp., Rept. No. R-203*, 27 pp. (*15th Aug.*, 1950). [Shortened version in *J. Amer. Rocket Soc.*, **21**, 179-185 (*Nov.*, 1951).]

The effect of chemical kinetics on rocket nozzle design is investigated for hydrogen flowing adiabatically through a nozzle having a chamber-to-throat area ratio of 2. Chamber temperature of 3500° K., pressure 20 atmos. and exit pressure 1 atmos. were assumed. Instantaneous equilibrium flow assumption gives highest specific impulse and requires largest nozzle. Kinetic equilibrium results are intermediate between those for instantaneous equilibrium and those for constant composition flow.

(225) **Mobile recording system, for rocket-motor tests.** K. C. SUTHERLAND and W. H. SPALDING. *Galcit Memo. No.* 4-61, 10 pp. (*4th Dec.*, 1950).

(226) **Motors that propel 3.5 inch rockets.** HERB. *Machinery*, 164 (*Jan.*, 1951).

(227) **The use of micro-rockets for the study of propellants.** M. BARRÈRE. *Rech. Aérodyn.* (21), 25-33 (*May-June*, 1951). (*In French.*)

The design of a micro-rocket system and discussion of results.

(228) **Combustion apparatus, including flame-type ignition means.** R. H. GODDARD. *U.S. Pat. No.* 2,569,887 (*2nd Oct.*, 1951).

(229) **Reaction motor operable by liquid propellants and method of operating it.** F. J. MALINA and J. W. PARSONS. *U.S. Pat. No.* 2,573,471 (*30th Oct.*, 1951).

(230) **Aspects of combustion stability in liquid propellant rocket motors. Pt. I.** L. CROCCO. *J. Amer. Rocket Soc.*, **21**, 163-178 (*Nov.*, 1951).

A formula is suggested correlating the time lag between propellant injection and transformation into gases with chamber pressure. This is used to determine critical conditions for a monopropellant system and it is shown that instability can occur even with constant rate of injection. It is also shown how the variation of injection rate affects the critical conditions. Finally the influence of non-uniform values of time lag is discussed.

(231) **Flame igniter for jet propulsion units.** F. A. PARKER. U.S. Pat. No. 2,574,495 (*13th Nov.*, 1951).

(232) **Fuel injector for rocket devices.** E. A. MAYNOR. U.S. Pat. No. 2,575,624 (*20th Nov.*, 1951).

(233) **Feeding and mixing means for rotating combustion chambers.** R. H. GODDARD. U.S. Pat. No. 2,576,678 (*27th Nov.*, 1951).

(234) **The auxiliary and take-off rocket B.M.W. 109-718.** H. GARTMANN. *Weltraumfahrt* (6), 134-139 (*Dec.*, 1951). (*In German.*)

History of the development and full technical details, including weights, performance data and propellant compositions.

(235) **Steady-state one-dimensional flow in rocket motors.** E. W. PRICE. *J. Appl. Phys.*, **23**, 142-146 (*Jan.*, 1952).

Solutions are presented for the problem of gas flow in a solid propellant rocket motor using combined numerical and graphical methods. Results are presented for the case of J.P.N. ballistite. These solutions give the equilibrium distributions of pressure, density, velocity and temperature of the gas stream and burning rate of the propellant.

(236) **The 1951 A.R.S. Annual Convention: a technical summary.** J. V. CHARYKI and G. SUTHERLAND. *J. Amer. Rocket Soc.*, **22**, 3-6, 27 (*Jan.-Feb.*, 1952).

A review of the 16 technical papers.

(237) **Aspects of combustion stability in liquid propellant rocket motors. Pt. II.** L. CROCCO. *J. Amer. Rocket Soc.*, **22**, 7-16 (*Jan.-Feb.*, 1952).

The problem of low-frequency combustion instability in bipropellant rocket motors is

analysed under the basic assumption that the time lag is affected by pressure variations. It is shown that for certain relations between the parameters of the two feeding systems the results of Pt. I (see Abs. No. 230) can be applied. Finally, using a simplified model for the spatial distribution of the combustion in the chamber, the case of high-frequency instability is analysed. The correlation between unstable and natural frequencies is shown, and the ranges of the time lag in which high-frequency modes become unstable are found.

(238) **Rocket applications of the cavitating venturi.** L. N. RANDALL. *J. Amer. Rocket Soc.*, **22**, 28-31 (*Jan-Feb.*, 1952).
Its applications as a simple and accurate flow control and as a temperature device are described.

(239) **Rocket propulsion progress: a literature survey.** G. P. SUTTON. *J. Amer. Rocket Soc.*, **22**, 17-27, 31 (*Jan.-Feb.*, 1952).
Reference is made to some 230 outstanding unclassified books and papers on general theory, propellants, research and instruction, rocket engines, rocket aircraft and assisted take-off units, guided missiles and rocket projectiles, military aspects, tests and operations and space travel.

(240) **Photographic techniques applied to combustion studies—two-dimensional transparent thrust chamber.** J. H. ALTSEIMER. *J. Amer. Rocket Soc.*, **22**, 86-91, 103 (*March-April*, 1952).
Motion pictures at 2,000 and 3,000 frames per second were taken of the combustion process for five different injector types. Stills are reproduced and curves shown for gas velocities versus axial distances from the injector faces.

(241) **Combustion studies with a rocket motor having a full-length observation window.** K. BERMAN and S. E. LOGAN. *J. Amer. Rocket Soc.*, **22**, 78-85, 103 (*March-April*, 1952).
A 1,200 lb. thrust combustion chamber with a $\frac{1}{4}$ inch wide window was used. The cameras were a 35 mm. continuous strip and a high-speed movie. Pictures are presented for the propellants ethyl alcohol and liquid oxygen under both stable and unstable operation.

ROCKET PROPELLANTS

(See also Abs. No. 201, 224, 227 and 239)

(242) **Method of producing hot gases for the purpose of jet propulsion.** *Aerojet Engng. Corp.*, Brit. Pat. No. 650,444 (*21st Feb.*, 1951).
Use of self-igniting fuels with nitric acid.

(243) **Index to documents dated prior to 1949 abstracted in S.P.I.A./A.L., A2, A3, A4, pertaining to American solid propellant research.** *Johns Hopkins University, Solid Propellant Information Agency* (*June*, 1951).

(244) **Investigation of chemical kinetics phenomena in rocket engines.** K. H. MUELLER. *Aerojet Engng. Corp., Prog. Rept. No.* 1056-2, 9 pp. (*24th Aug.*, 1951).

(245) **Propellant having an opacifier for preventing self-ignition by radiant energy radiations.** C. N. HICKMAN. U.S. Pat. No. 2,574,479 (*13th Nov.*, 1951).

(246) **Propellant charge.** *Aerojet Engng. Corp.*, Brit. Pat. No. 660,789 (*14th Nov.*, 1951).

(247) **Quantitative evaluation of rocket propellants.** S. S. PENNER. *Amer. J. Phys.*, **20**, 26-31 (*Jan.*, 1952).
Review of the methods for the theoretical calculation of propellant performance.

(248) **The effects of several variables upon the ignition lag of hypergolic fuels oxidised by nitric acid.** S. V. GUNN. *J. Amer. Rocket Soc.*, **22**, 33-38 (*Jan.-Feb.*, 1952).
A method is described for measuring the ignition lag of self-igniting bipropellant combinations. Ignition lag data are reported for combinations of nitric acid with aniline, furfuryl alcohol, and their mixtures. Ignition lags range from about 10 to 400 milliseconds, depending on temperature, acid composition, fuel composition and metallic additives (12 refs.)

(249) **Calculation of adiabatic decomposition temperatures of aqueous hydrogen peroxide solutions.** G. C. WILLIAMS, C. N. SATTERFIELD and H. S. ISBIN. *J. Amer. Rocket Soc.*, **22**, 70-77 (*March-April*, 1952).
The technique of calculation is described and graphical presentations are given of the temperature, and liquid and vapour compositions as a function of the fraction of hydrogen peroxide decomposed for several initial concentrations and at several pressures.

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